

Advanced Electrical Power Systems

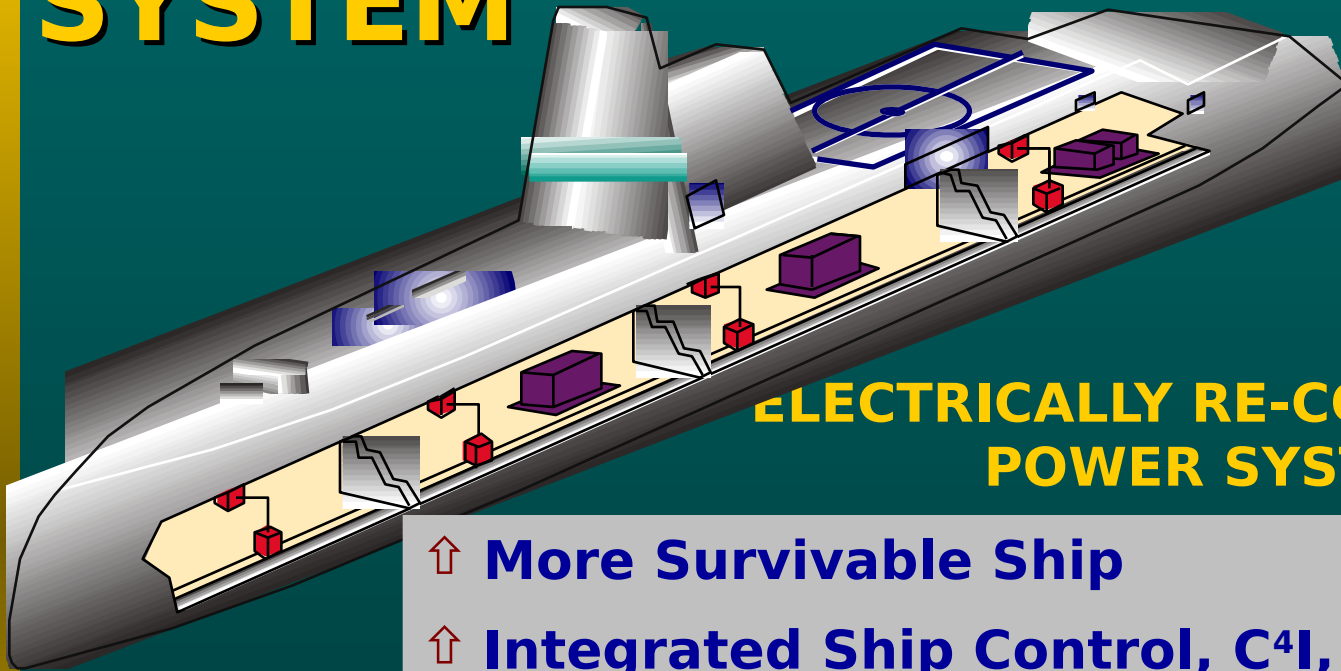
**Terry
Ericsen**

**Concepts,
Technologies,
and
Architectures**

Mr. Ericsen is an Electrical Science & Technology Program Officer at the Office of Naval Research. The views presented are those of the author and do not necessarily represent the views of DoD or its components.

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“NAVY AFTER NEXT” POWER SYSTEM



**ELECTRICALLY RE-CONFIGURABLE
POWER SYSTEM ENABLES:**

- ↑ **More Survivable Ship**
- ↑ **Integrated Ship Control, C⁴I, Engineering Plant, and Damage Control Systems**
- ↑ **Leverage of commercial technology continuously upgraded modular architectures (hardware and software)**
- ↑ **Near Zero Emission of NOX, SOX, ... Pollutants**

Technical Strategy

S&T CHALLENGES

PHYSICS-BASED MODELS OF
POWER NETWORKS;
SIMULATION OF TOTAL SHIP
POWER SYSTEMS

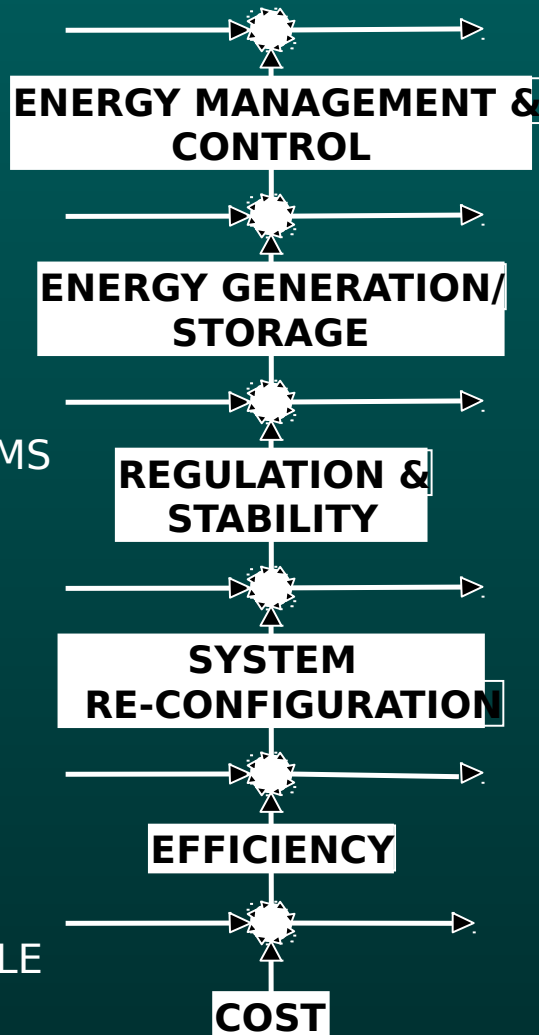
DISTRIBUTED POWER
GENERATION,
RAPID POWER TRANSFER,
ENERGY STORAGE

INTEGRATED CONTROL
METHODOLOGIES, ALGORITHMS
& ARCHITECTURES

ACTIVE FILTERING FOR NON-
LINEAR AND PULSING LOADS

CONTROL THERMAL,
MECHANICAL, ELECTRICAL
LOSSES

MODULAR LEAST REPLACEABLE
UNITS



SYSTEM PAYOFFS

Dynamic
Reconfiguration of
Electric, Auxiliary &
Damage Control
Systems, Full
High Power Electric Weapons
Automation
Sensors & Countermeasures

Dynamic Reconfiguration
of
Electrical Systems,
Reduced Manning
Fight Thru Power for All
Mission Critical Functions

Increased Power Density,
Reduced Signatures

Reduced Acquisition Cost &
Total Ownership Cost

Programmatic Strategy

- Procure custom quantities from high volume production lines.
- Build Navy requirements into high volume productions lines -- Navy ready COTS.
- Leverage commercial R&D investments
- Use global foundries to reduce cost and increase performance
- Build Navy systems based on pre-engineered, pre-tested, commercially applied building blocks instead of one-of-kind system developments

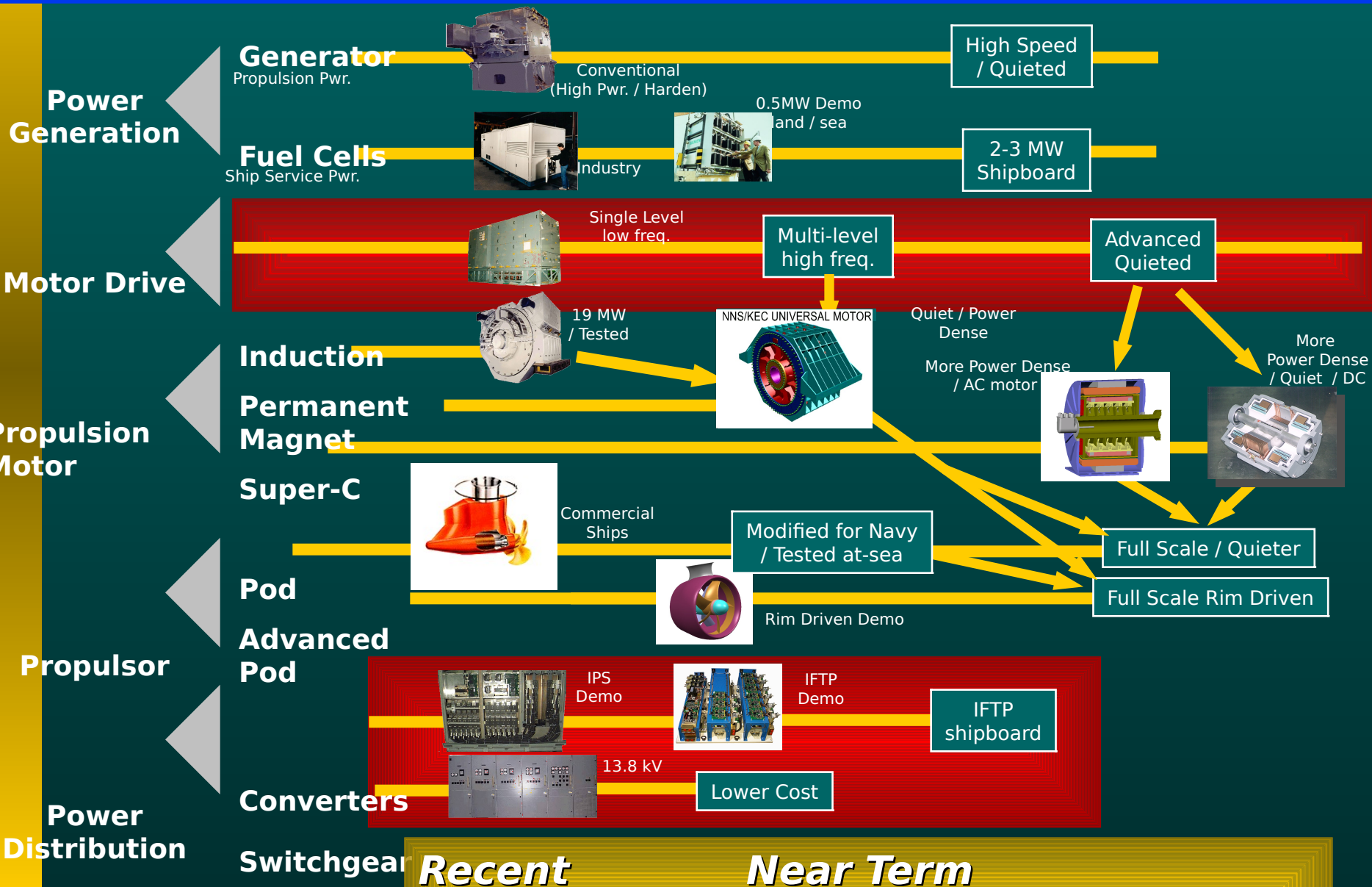
The Navy needs to buy hundreds of units from production lines that produce multi-millions of

Unique Navy Requirements

- Quiet operation
- Power Quality -- 3% THD, Total Harmonic Distortion (Utility ~13% THD)
- High Impact shock
- Power Density
 - Navy has to have it
 - Commercial would like to have it

Need another 10x reduction in Size, Weight, and Cost (??)

Potential Electric Warship Technology Areas



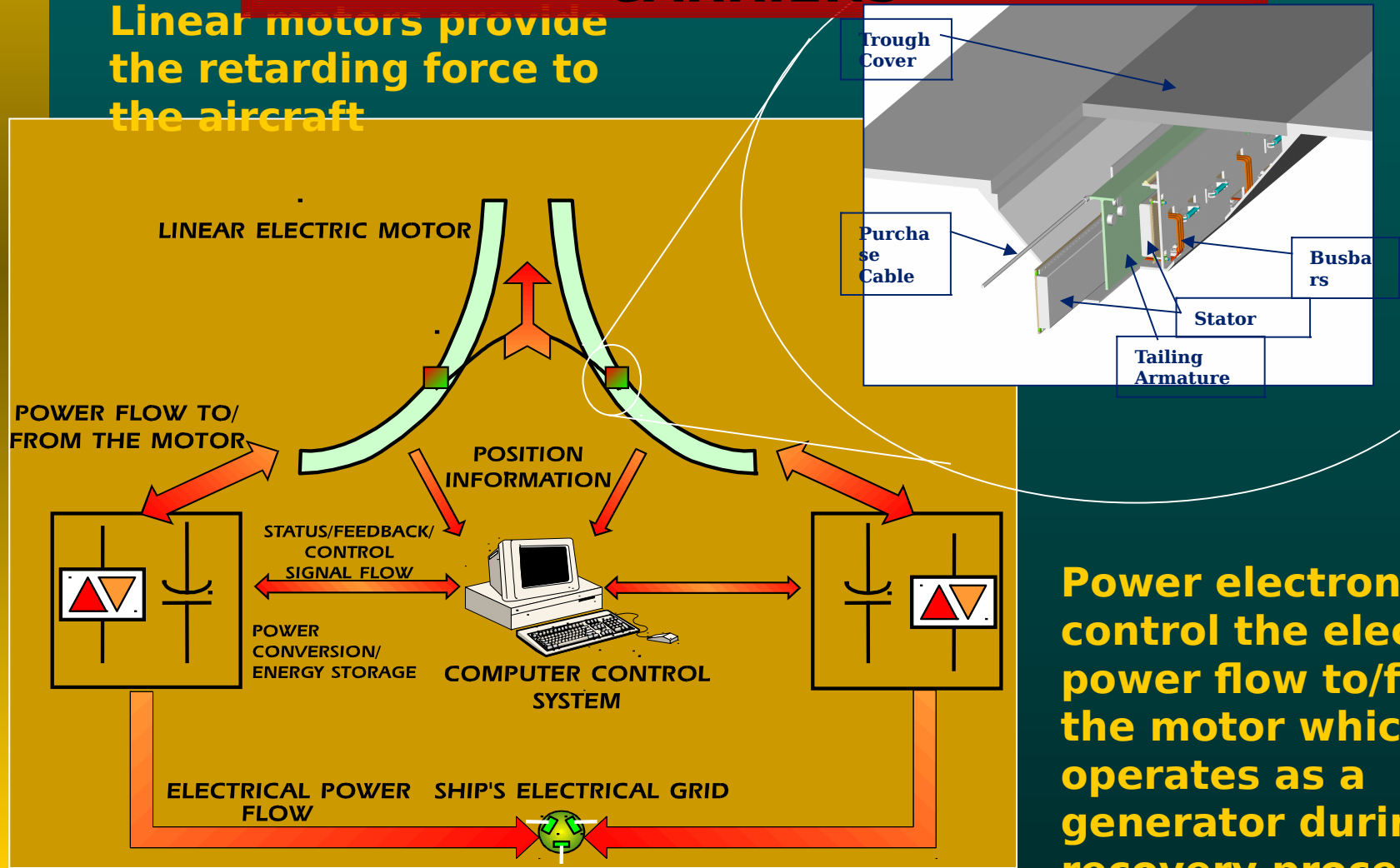
Advanced Electric Power Systems

- Advanced Linear Motor, ALM
- Ship Service Fuel Cell
- Power Electronics
- Advanced Electrical Systems

ALM Concept

REVOLUTIONARY APPROACH TO RECOVER AIRCRAFT ON CARRIERS

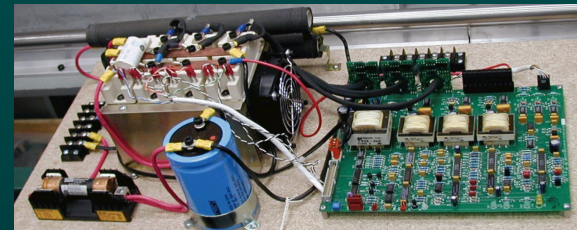
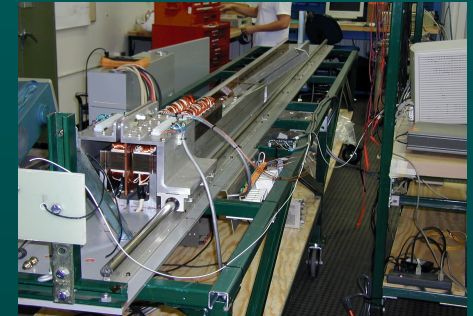
Linear motors provide
the retarding force to
the aircraft



Power electronics
control the electrical
power flow to/from
the motor which
operates as a
generator during the
recovery process

Advanced Linear Motor Demonstrations

- Demonstrate dual-sided recovery system (FY99)
- Develop and test scale linear motor of proposed design (FY00)
- Develop and test scale power conversion system of proposed design (FY99/00)
- Demonstrate high bandwidth control of two independent motors (FY99)



ALM Benefits

***Eliminates the Legacy Design Cycle
Enables the Expansion of the Design Trade
Space
for Optimized Ship and Aircraft Designs***

Affordability

- Savings of up to 1675 man hrs/week/ship - reduced operator and maintenance requirements
- Eliminate hazardous materials - clean-up and storage cost savings
- Reduce Wind-Over-Deck requirement resulting in propulsion fuel savings

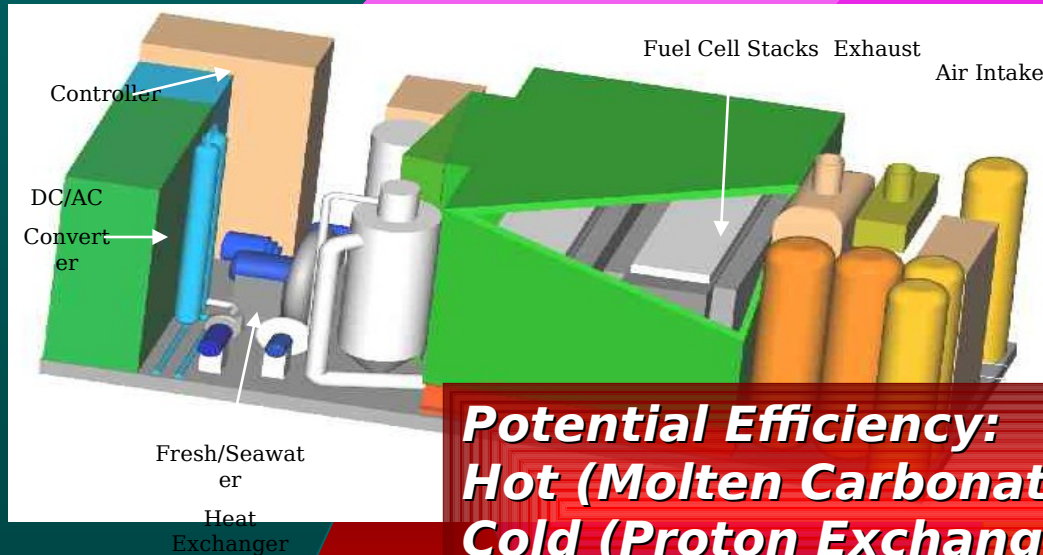
Performance

- Increase energy capacity by 60%
- Increase engaging speed by 20%
- Enable the recovery of small, lightweight aircraft (UAVs/UCAVs)
- Operate in degraded modes (safety, arresting engine availability)

Ship Design Flexibility

- Opens up design trade space for placement of hardware (modular components)
- Facilitates All-Electric Ship
- Reduce weight and volume

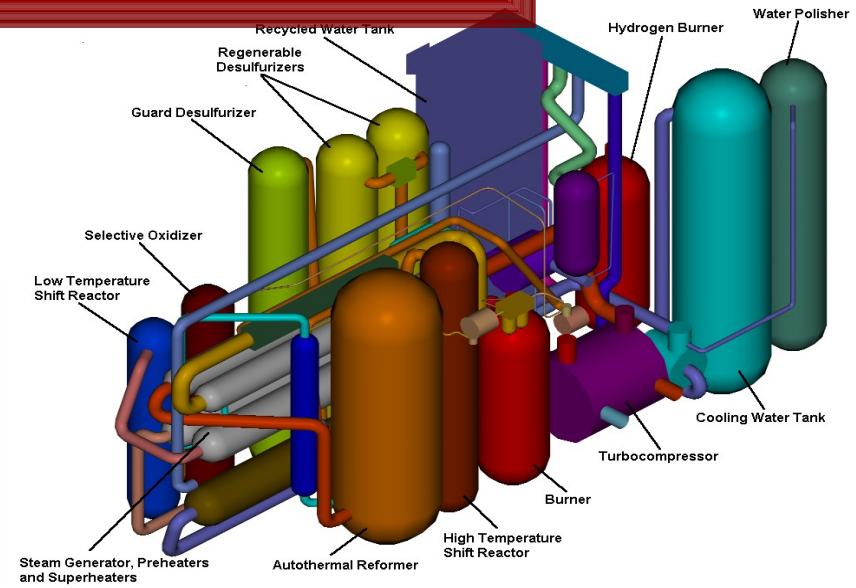
Ship Service Fuel Cell



FuelCell Energy
625kW 450V, 3 ϕ , 60
HZ, MC SSFC Power
System

Potential Efficiency:
Hot (Molten Carbonate) = 60-70%
Cold (Proton Exchange Membrane)
= 40%

McDermott Technology
500kW SSFC Integrated
Fuel Processor (IFP) --
Autothermal Reformer



Navy Shipboard Fuel Cell Program Estimate of Fleet Savings



DD963 Class: 24 Ships, L563',
9100T
CG 47 Class: 27 Ships, L567',
9600T
DDG51 Class: 27 Ships, L510',
9000T

GTG Plant
2.5 MW GTGS
(3) Per ship

Fuel Cell
Plant
2.5MW Fuel Cell
(3) Per ship

Savings

Ownership Cost for 78 GT Ships:

Annual Fuel Cost (\$M)
147

Annual Maint. (hrs)
245,746

UNREPs* Per Ship 20
(Avg. 180 day deployment)

Exhaust:

Flow (lb/sec) per generator
33

Temperature (°F) @100% Load 1050

Emissions (NOx ppm) @100% Load

49
172,926
15

6.7
350
.01

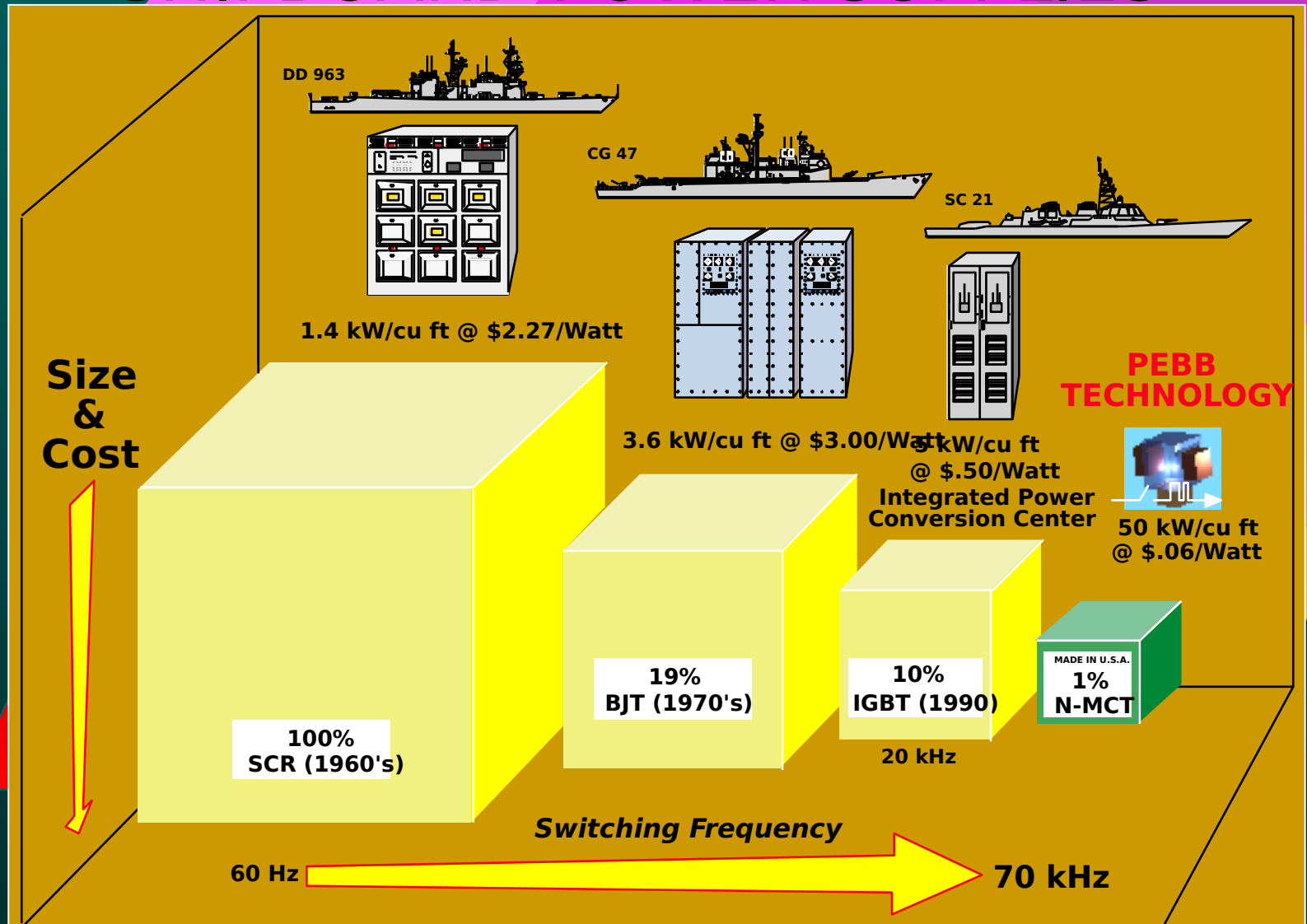
\$98 M
72,820 hrs
5
UNREPS

26.3
lb/sec
700 °F
282.9 ppm

*UNREPS = underway replenishments

Power Electronics

SHIPBOARD POWER SUPPLIES



Summary of Accomplishments

- > 100 patents
- IEEE Power Engineering Society Working Group 18, Power Electronic Building Blocks Concepts -- substation subcommittee
- 9 MVA 3-terminal PEBB in two applications in 20MWatt rating range
 - 18 MVA Frequency Changer, German railway -- in service
 - 20 MVA Dynamic Voltage Restorer, Israeli IC Manufacture -- in service
- Rockwell 700 series Industrial Drives -- product announcement
- ON-Switch -- Near perfect for “Smart Munitions”

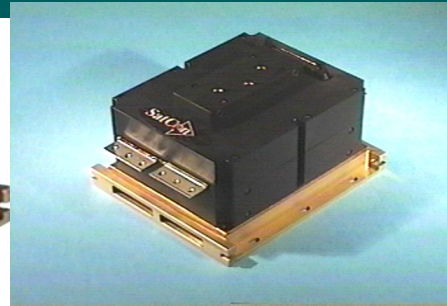
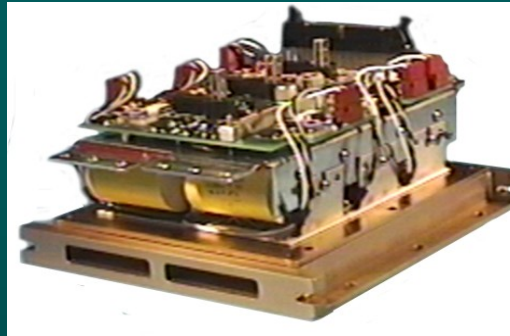
Program Goals

		Initial	Today	Goal
Power Density	kW/ft ³	5	50-600	50
Turn-Off Current	A/cm ²	50	300	500
Turn-On di/dt	A/nsec	~1	1500	10
Turn-Off Time	nsec	1200	400	120
Off State	Volts	1000	6500	3500
Switching Frequency	kHz	5	~10-20	70

PEBB Form (blocks)

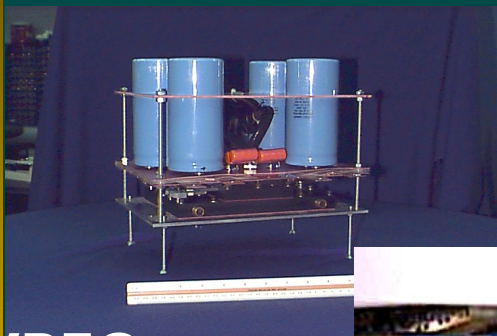
All Power Densities Exceed Program Goals

- Low Power, < 50kW

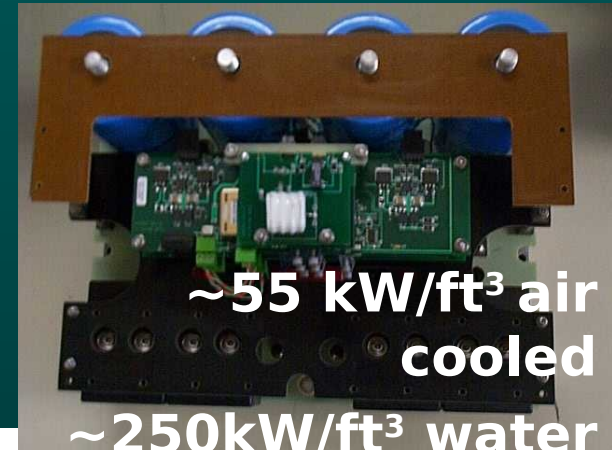


Satcon,
~600 kW/ft³

- Medium Power, 50kW - 1MW



CDNSWC/SPCO,
~60 - 80 kW/ft³



~55 kW/ft³ air
cooled

~250kW/ft³ water
cooled

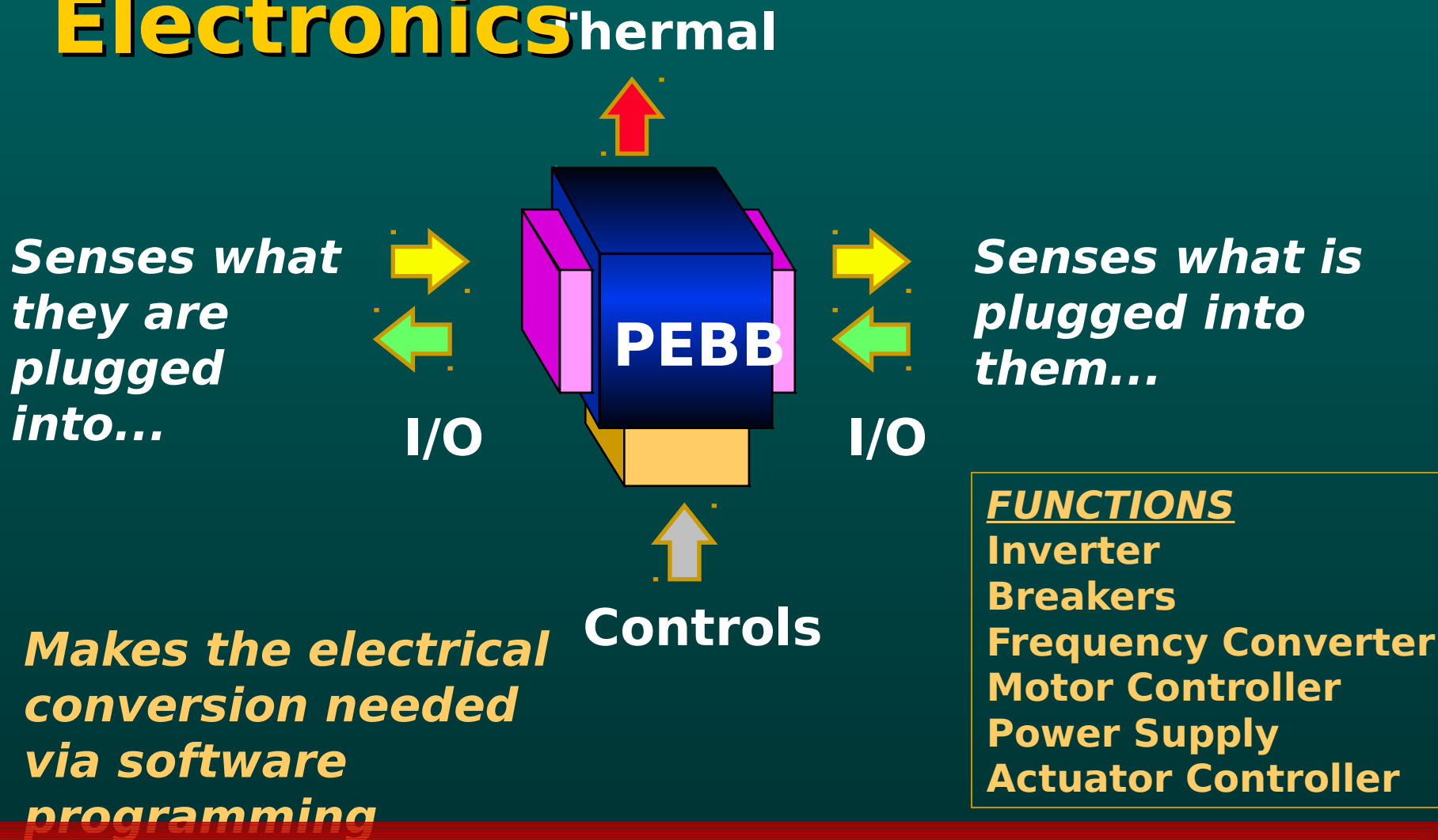
VPEC,
~50-100 kW/ft³



SPCO/Northrop-
Grumman

***Another factor of 10 is possible in
silicon more in silicon carbide***

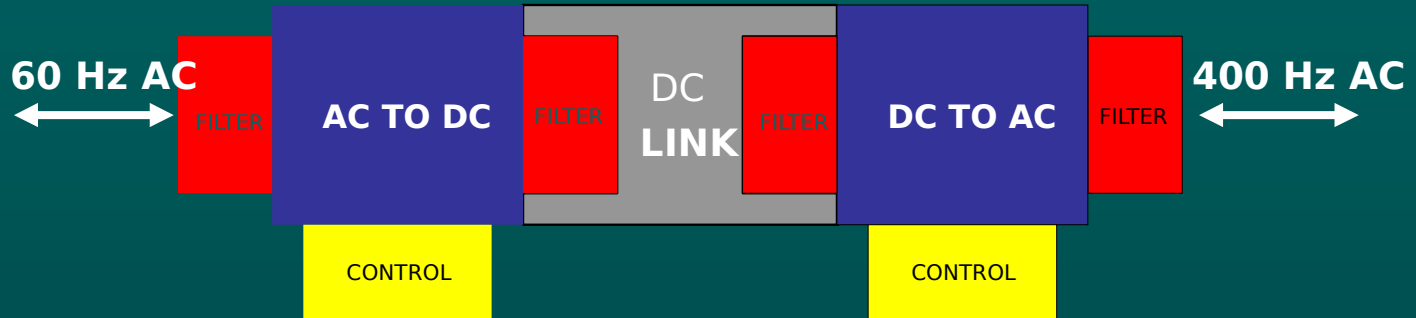
PEBB Systems: A Simple Set of Blocks for Power Electronics



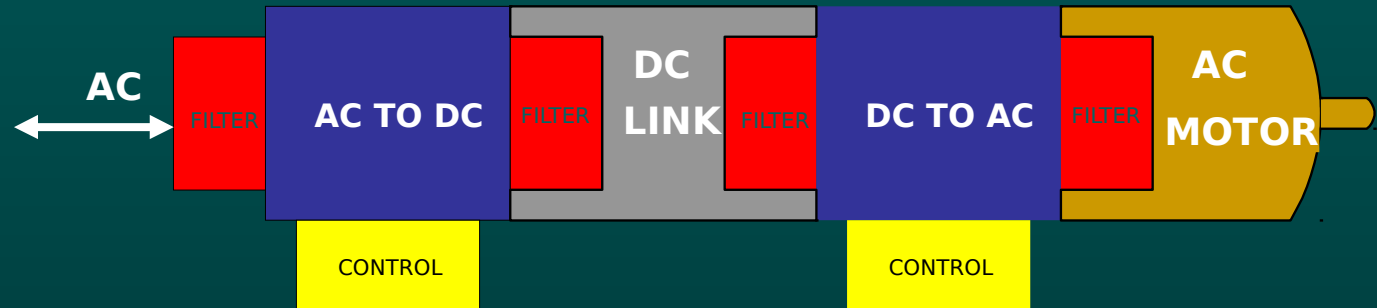
Like a child's set of blocks

A Simple Set Of Blocks For All Power Needs

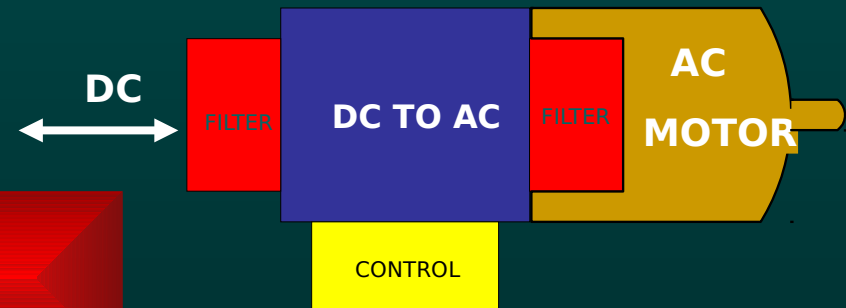
**FREQUENCY
CONVERSION
USING TWO
PEBB
INVERTERS**



**AC TO AC
MOTOR
CONTROLLER
USING TWO
PEBBS**

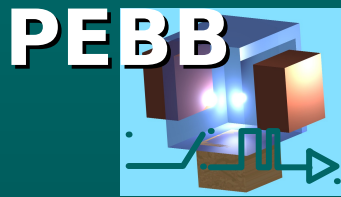


**MOTOR
CONTROLLER FROM
A DC SOURCE**



***“Open Plug and Play
Architecture”***

***“Like a child’s set of
blocks”***

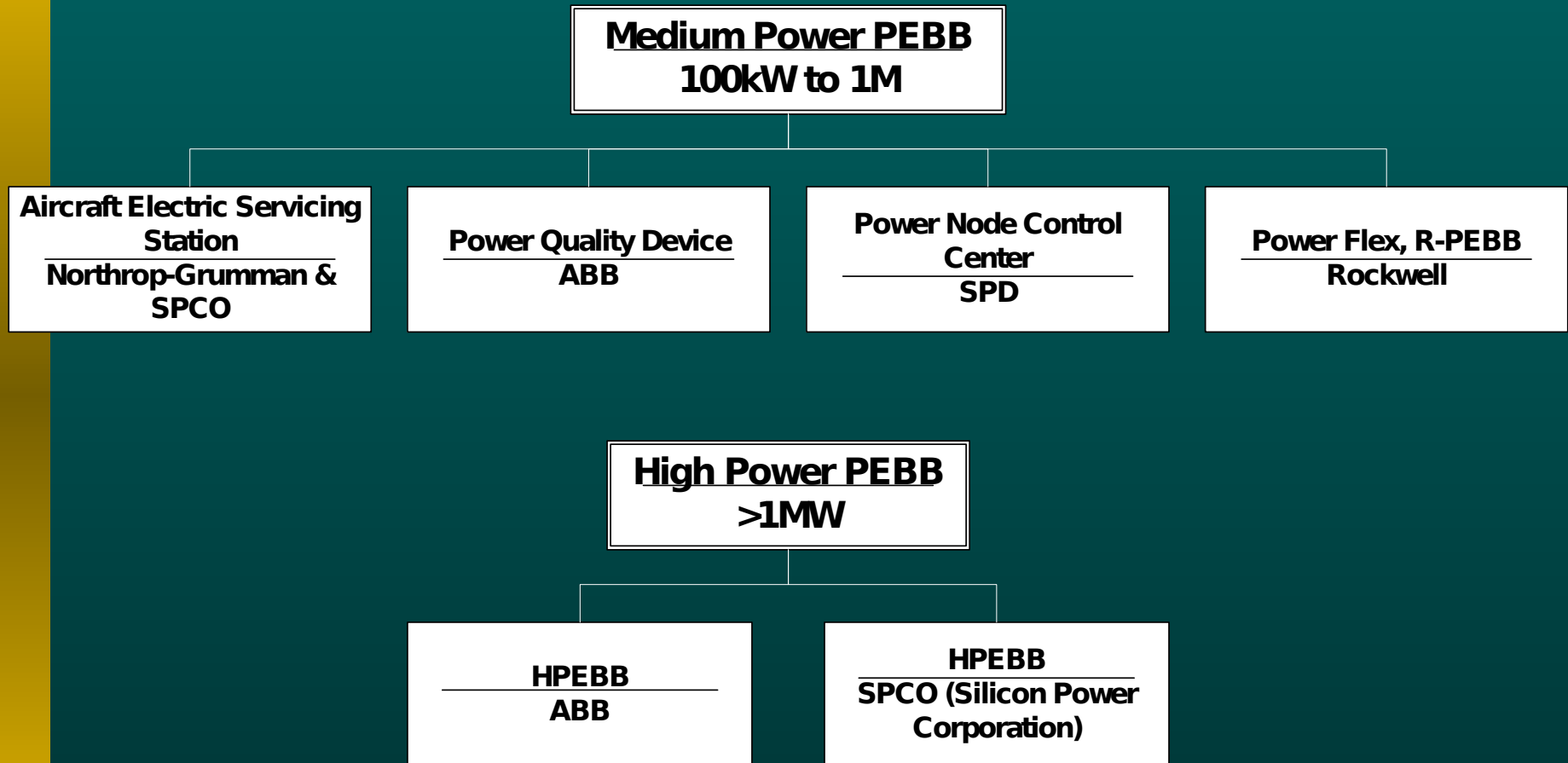


Types of Blocks

- Power Switching Blocks
 - 2-terminal - AC switch
 - - 3-terminal - phase legs
 - 5-terminal - bridge
 - 9-terminal - matrix
- Control Blocks (Universal Control Architecture)
 - System Controller
 - - Application Manager
 - Hardware Manager
 - Component Manager

- Filter Blocks
 - AC
 - DC
- Storage Blocks
 - Inductor
 - Capacitor
 - Electro-chemical
 - Electro-mechanical
- Motor Blocks
- Actuator Blocks
- Fuel Cell/Generator Blocks

REAL PEBB Products



Parallel Development Paths

Learned -- Integration

- Modularity generally increases size, weight, and cost.
- Modularity that enables integration can lead to far lower cost, size, and weight
- Attributes of integration based modularity
 - Physics basis for partitioning ---thermal, mechanical and electrical
 - Cellular design -- material-to-system design rules
 - Programmable - increased performance with existing hardware and reconfiguration

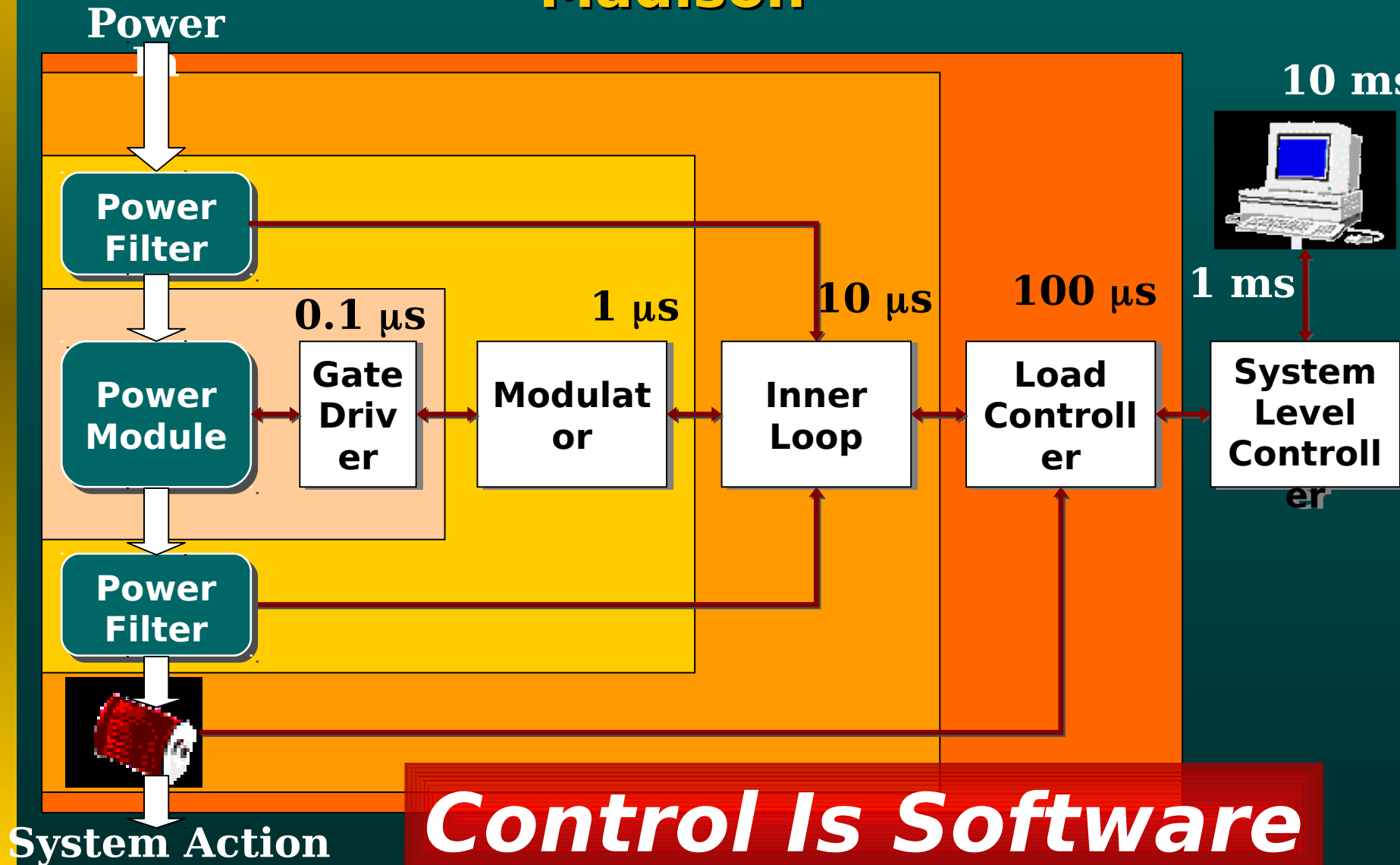
Refined -- Concept/Steps (Factors Affecting Partitioning)

- **Functional Distribution**
 - Power stage topology
 - Application requirements
 - Control algorithms
- **Temporal Distribution**
 - Protection requirements
 - Switching frequency and modulation algorithms
 - Time constants and control bandwidth
- **Spatial Distribution**
 - Power level
 - System requirements

Formed -- A Universal Controller Working Group

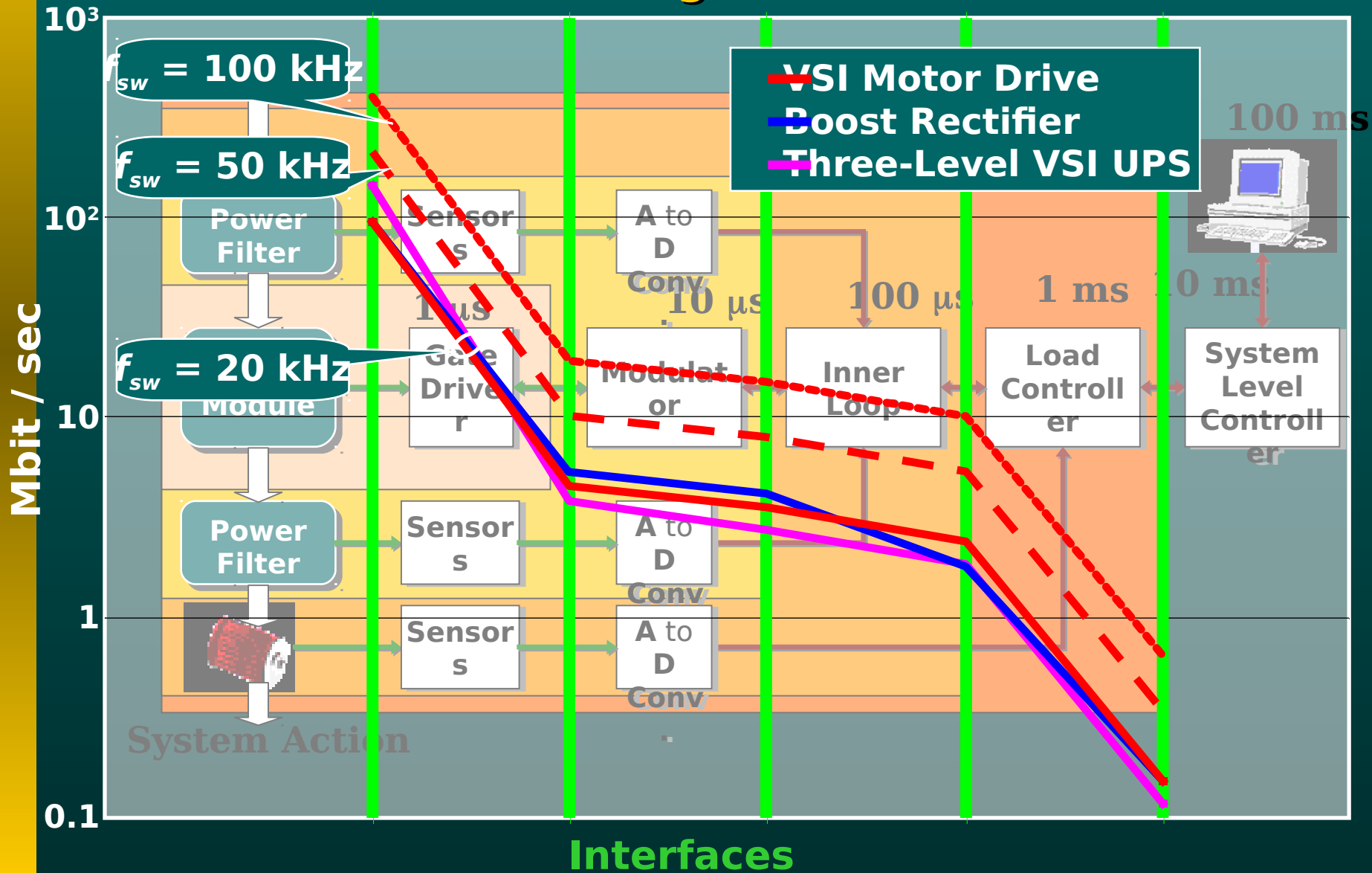
- NSWC -- Philadelphia
- Virginia Tech
- Northrop-Grumman
- Silicon Power Corporation
- Penn State
- Kaman
- Bettis Lab
- General Dynamics Defense Systems
- Newport News Shipbuilding
- Rockwell
- ABB
- Airak Inc.

As A Result - Universal Controller Architecture, CPES, U of Wisconsin - Madison



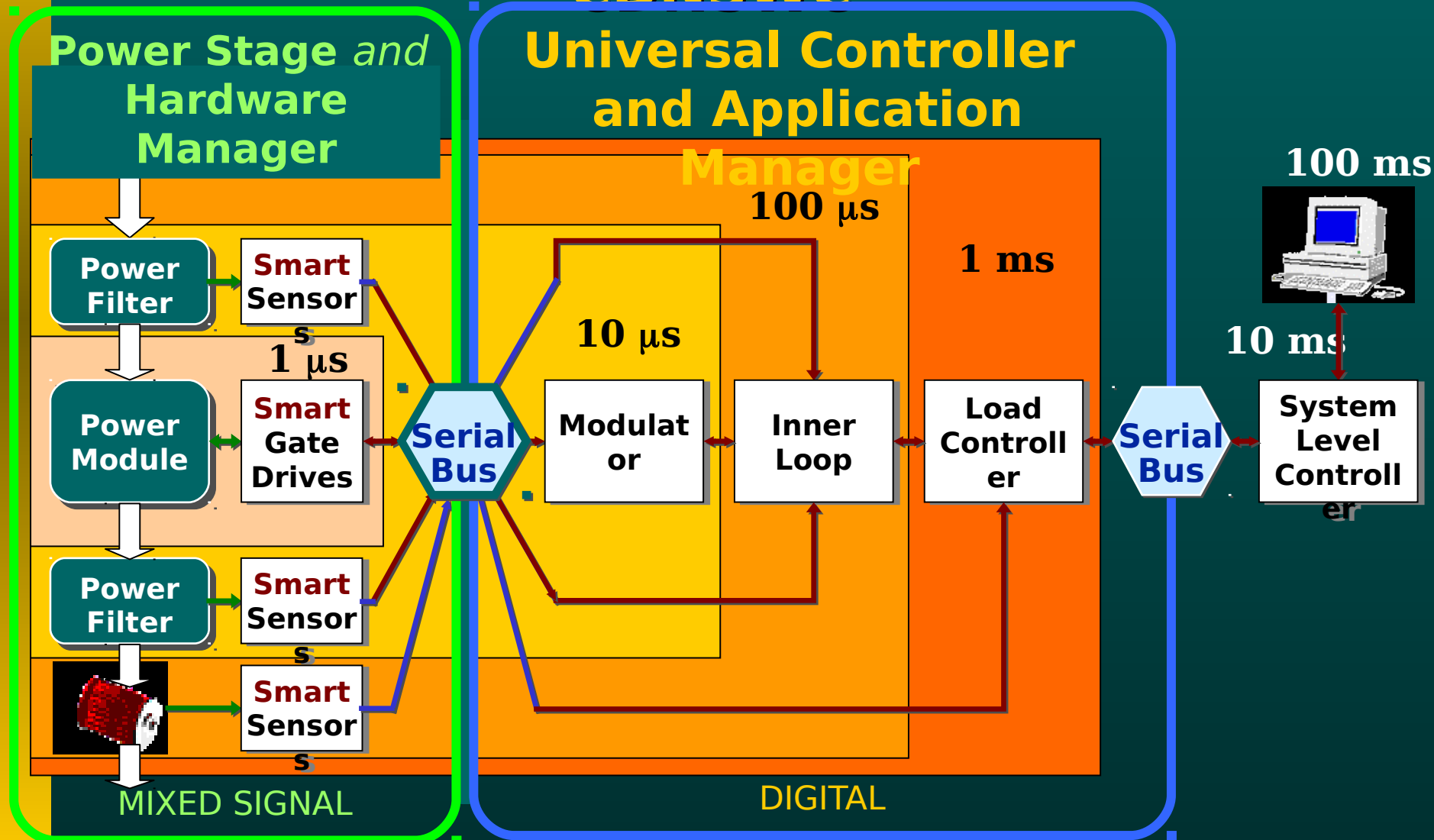
Required Interface Capacity

Sample Three-Phase Applications,
CPES, Virginia Tech



Universal Controllers under Consideration

with serial bus interfaces, CPES & CDNSWC



TODAY'S NODES CONSIST OF A
COLLECTION OF THE FOLLOWING:

LIGHTS

CT

PT

PROCESSOR

RELAYS

INSTRUMENTS

SWITCHES

DETECTORS

RECORDERS

CIRCUIT
BREAKERS

TRANSFER
SWITCHES

DISCONNECT
SWITCHES

MOTOR
CONTROLLER

RECTIFIERS

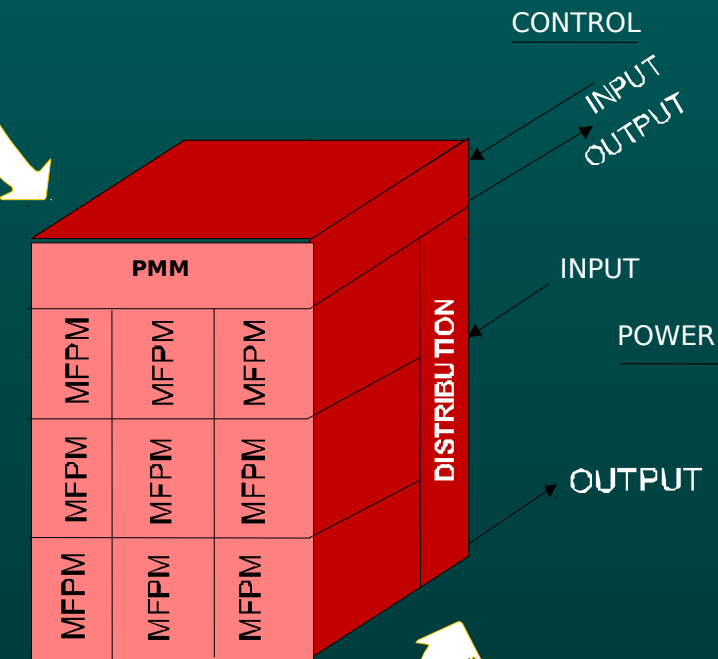
INVERTER
S

TRANS-
FORMER

ASD

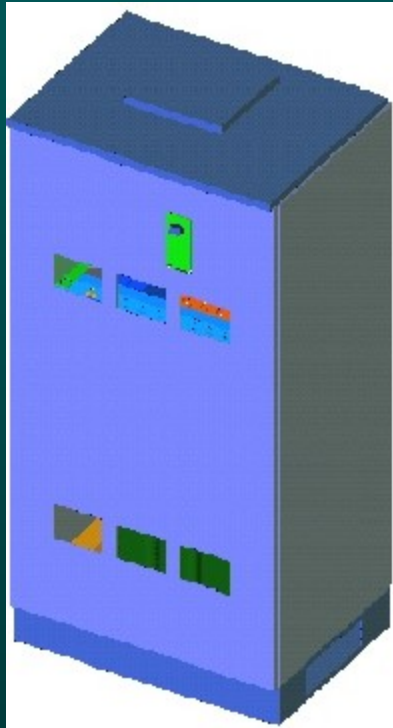
DISTRIBUTION BUS

TOMORROW'S NODES WILL BE
STANDARDIZED, PRE-
ASSEMBLED PACKAGES



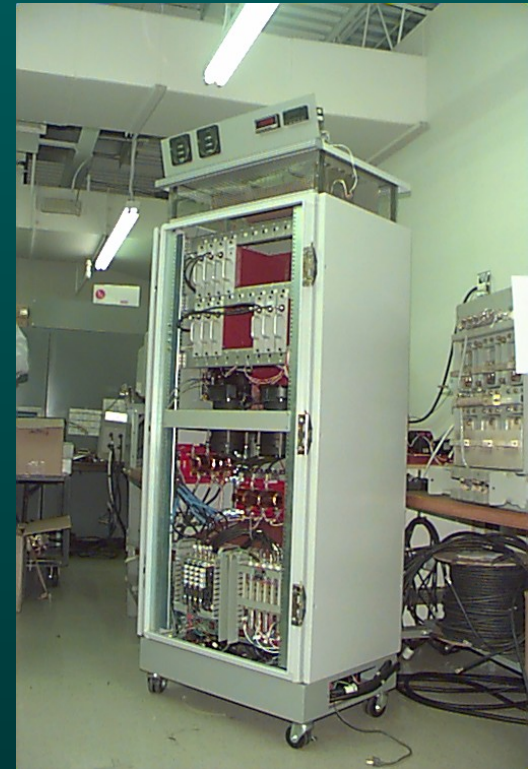
Power Node Control Center

Concept

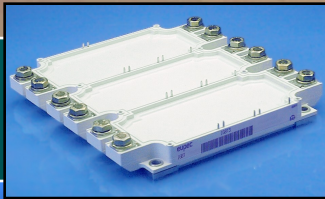
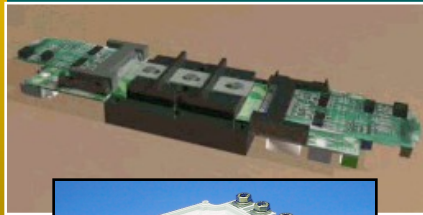


Feasibility
Demonstrator
72"x24"x30"

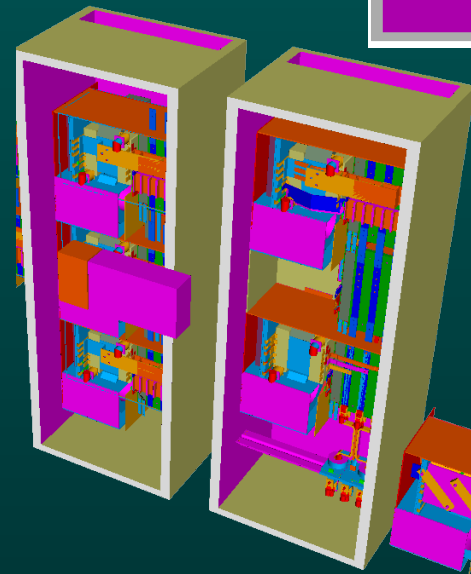
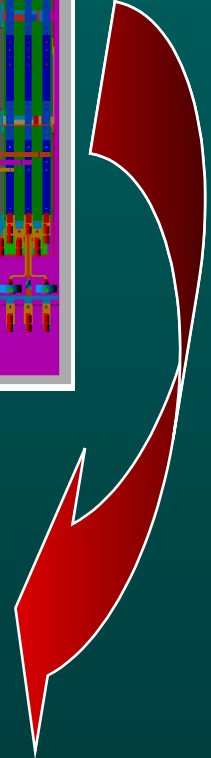
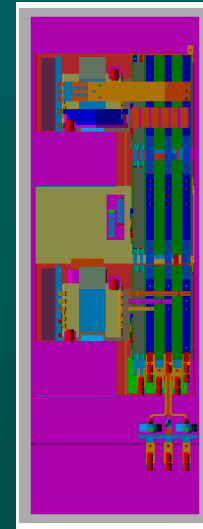
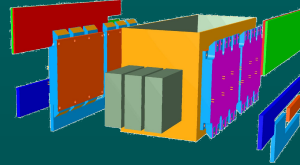
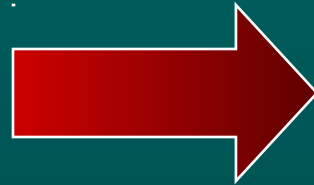
Hardware



Rockwell, R-PEBB



**Future
R-PEBB
CELLS**



Standard Cell Based Drives Structure

- 45% Power Efficiency Improvement
- Allows cellular upgrades without platform destruction
- Able to Adapt Previous PEBB Technology
- **FY1999 Goal: 40 % Decrease in \$ / amp**

Rockwell PowerFlex Product Family

PowerFlex
Powerful Performance. Flexible Control.

PowerFlex
Powerful Performance. Flexible Control.
7000

PowerFlex
700

PowerFlex
70



R-PEBB



New R-PEBB Product due 1Q 2001, built on

ABB HPEBB Dual Use Program

High Power Applications

**ABB HPEBB 9 MVA
Phase Leg**

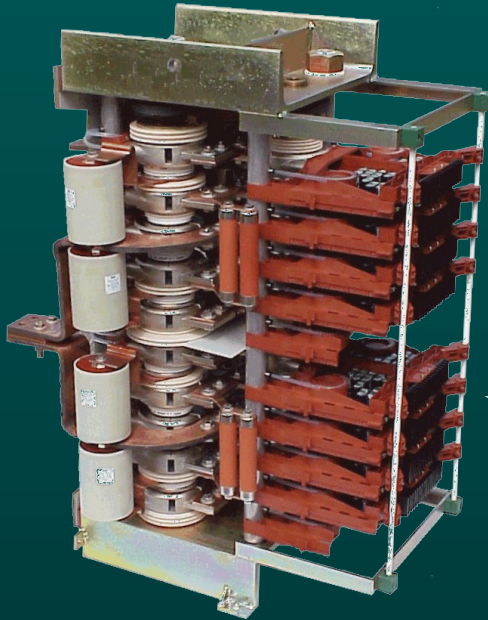
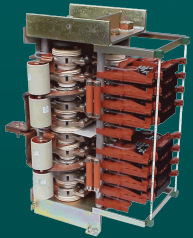


**ABB 18 MVA
Frequency
Changer**



ABB HPEBB Dual Use Products

ABB HPEBB 9 MVA Phase Leg



**Installed
Inter-Tie**

**ABB 18 MVA
Frequency Changer**

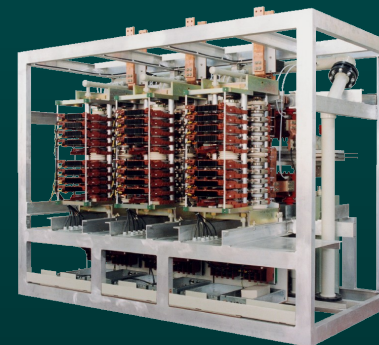
**+ 10
months**

Systems

- **Inter-Tie/Frequency Changer**
- **DVR - Dynamic Voltage Restorer**

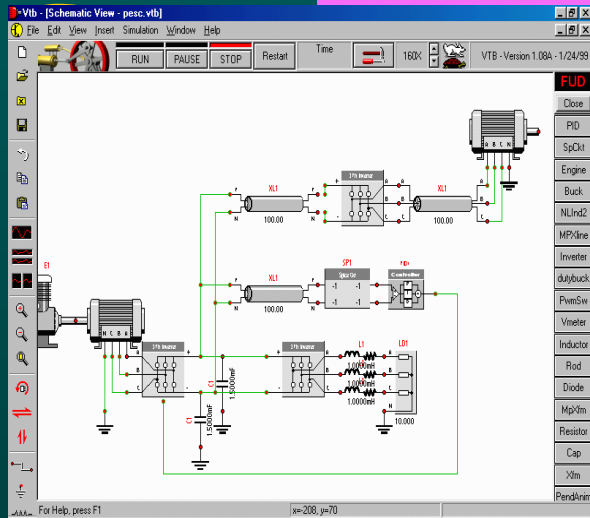
- **Drives**
- **Power Quality Products**

(~ 3 months after the Inter Tie)

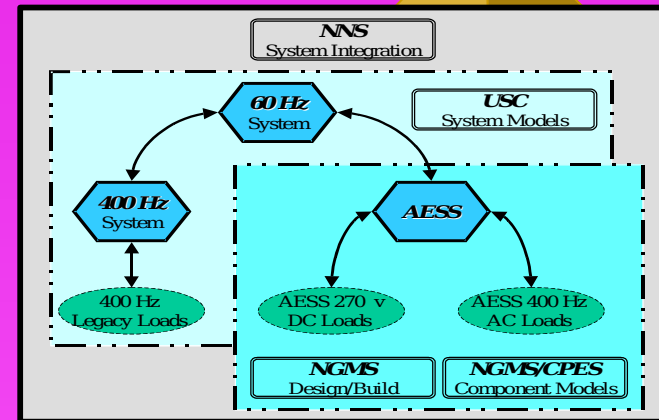


20 MVA DVR

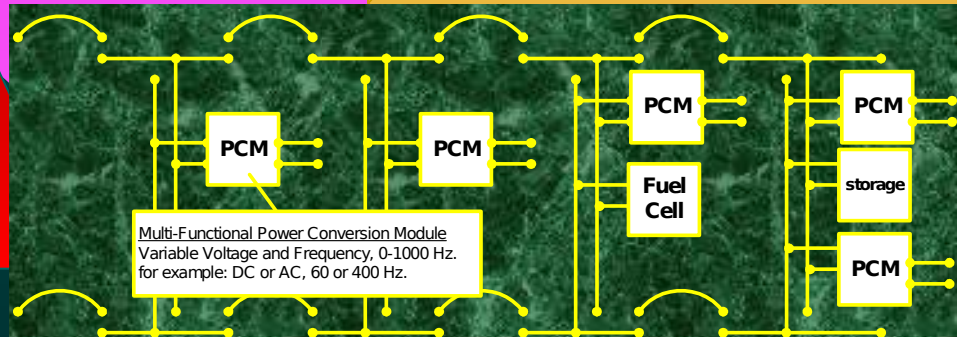
Advanced Electrical ns



Virtual Test Bed

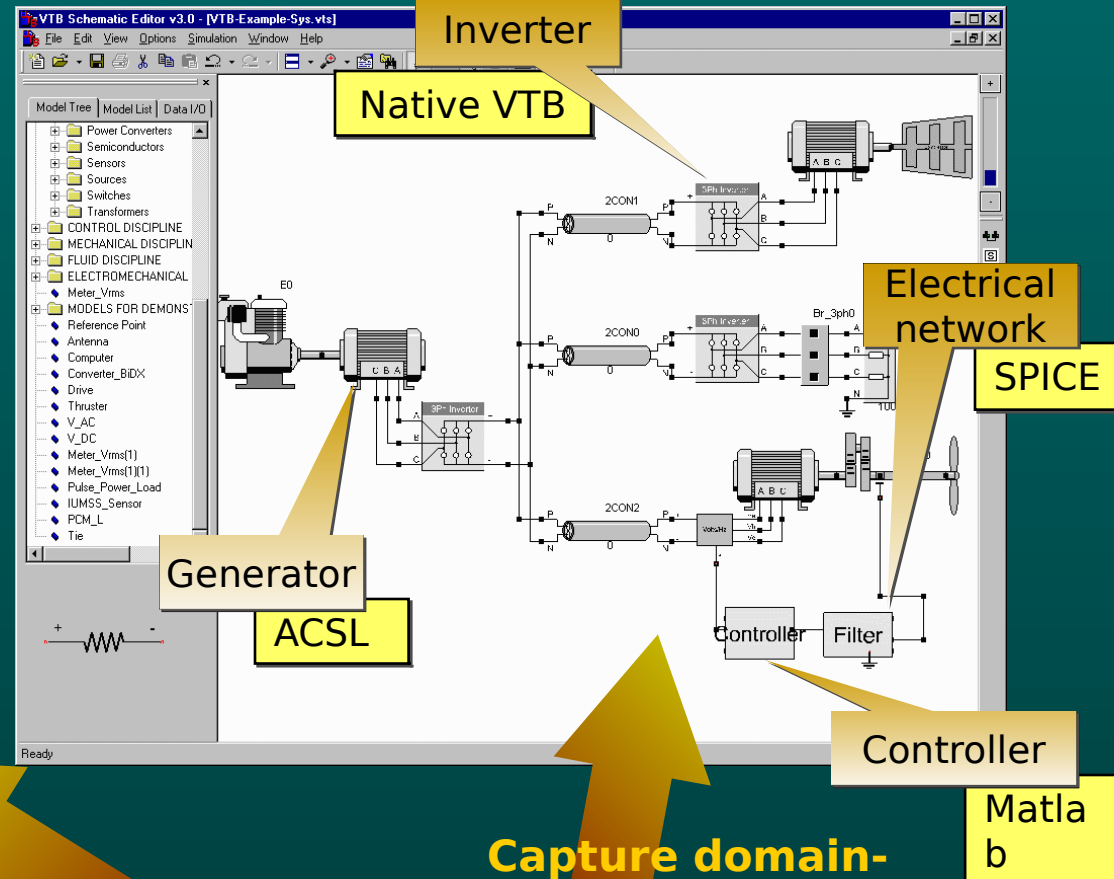
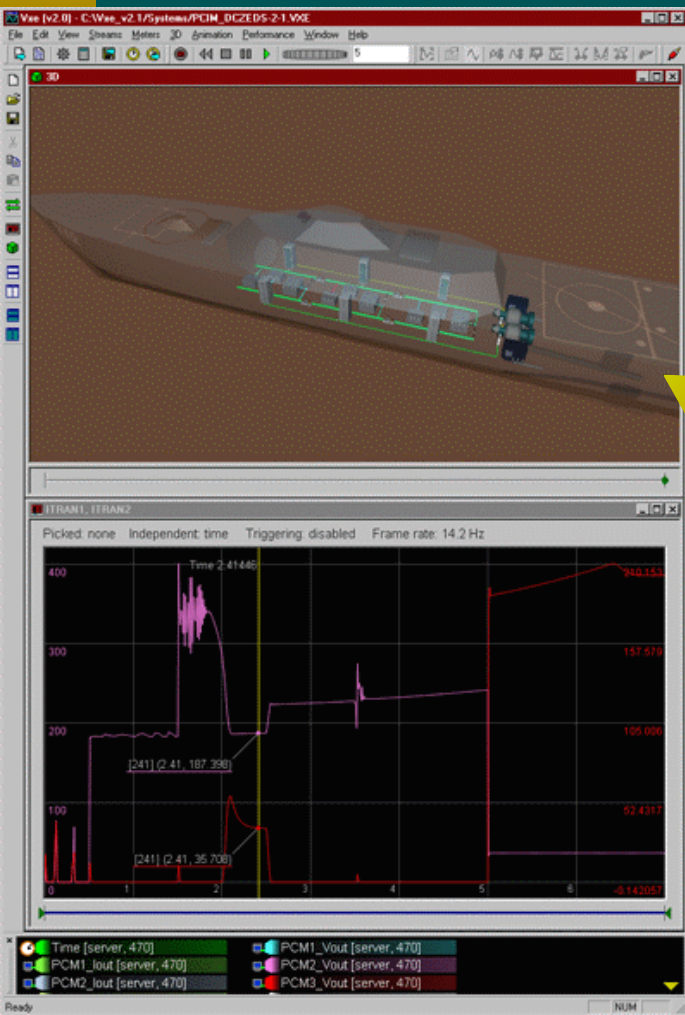


**Aircraft Electric Servicing Station,
AESS**



Point of Use Power Conversion

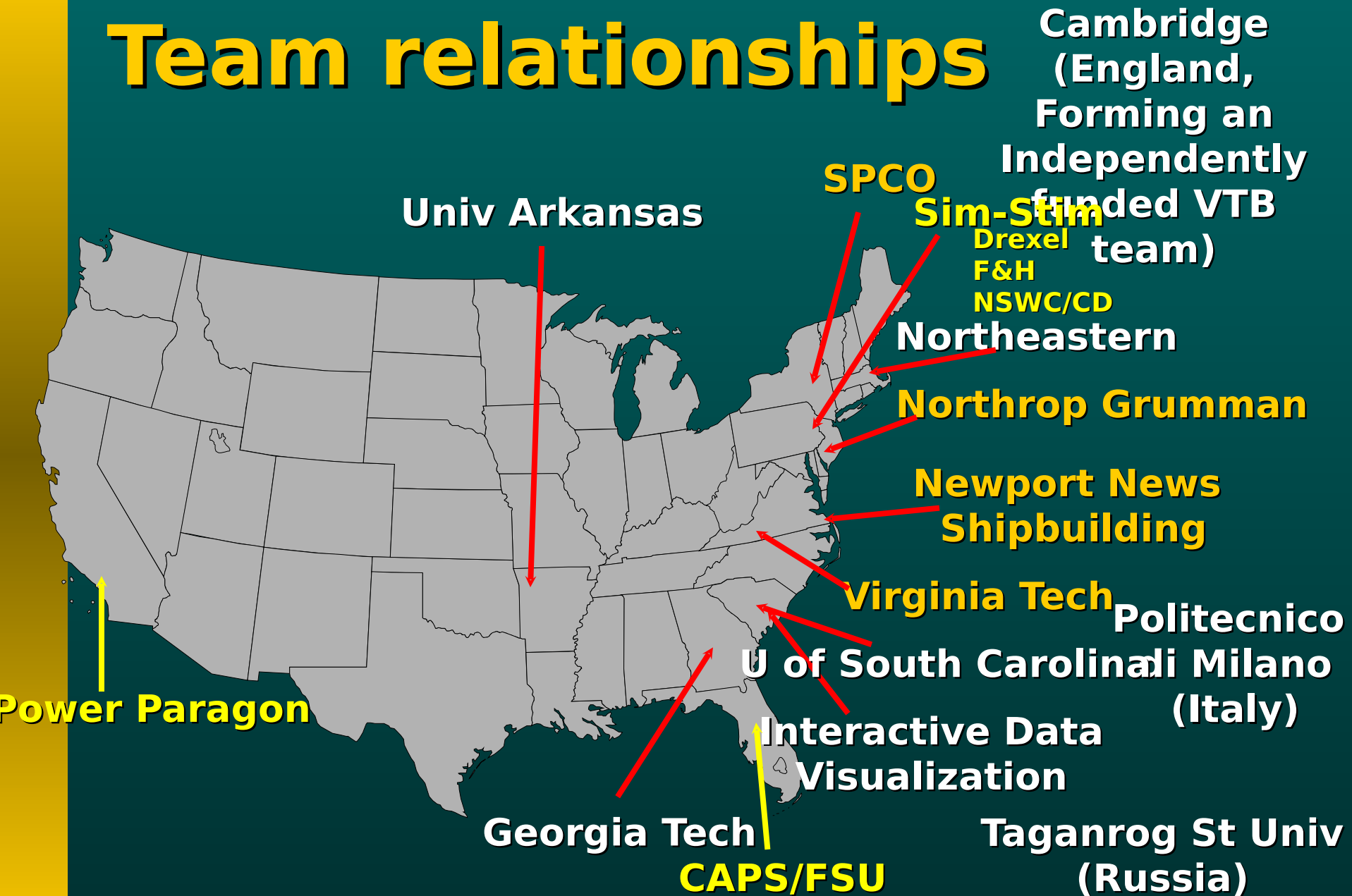
Virtual Test Bed, U of South Carolina



Capture domain-specific expertise in simulation models, Advanced visualizations preserve utility of existing models and increase comprehension of modeling skills

A software environment for virtual prototyping of systems of complex dynamic systems.

Team relationships



Aircraft Electric Servicing Station



Newport News Shipbuilding
(NNS)



(CPES)



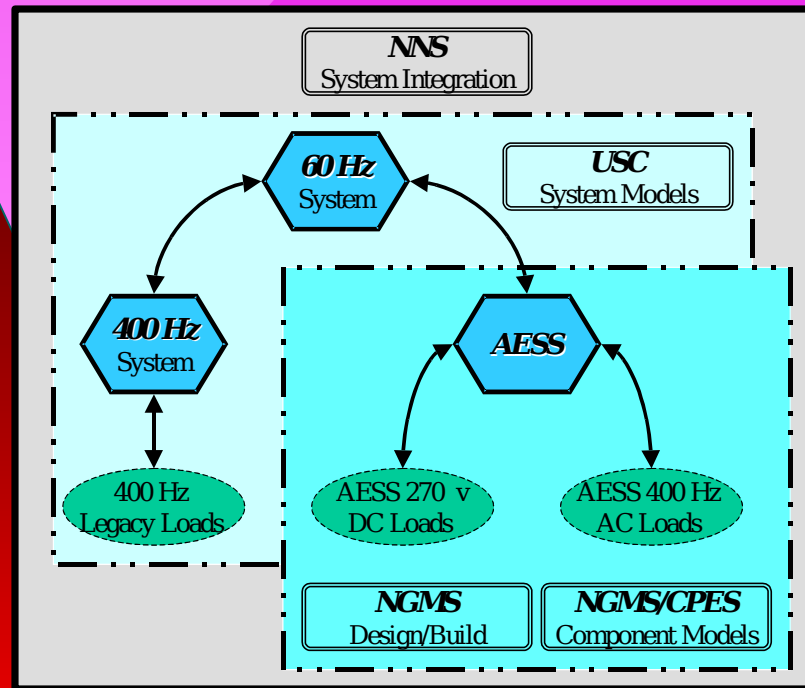
UNIVERSITY OF
SOUTH CAROLINA

(USC)

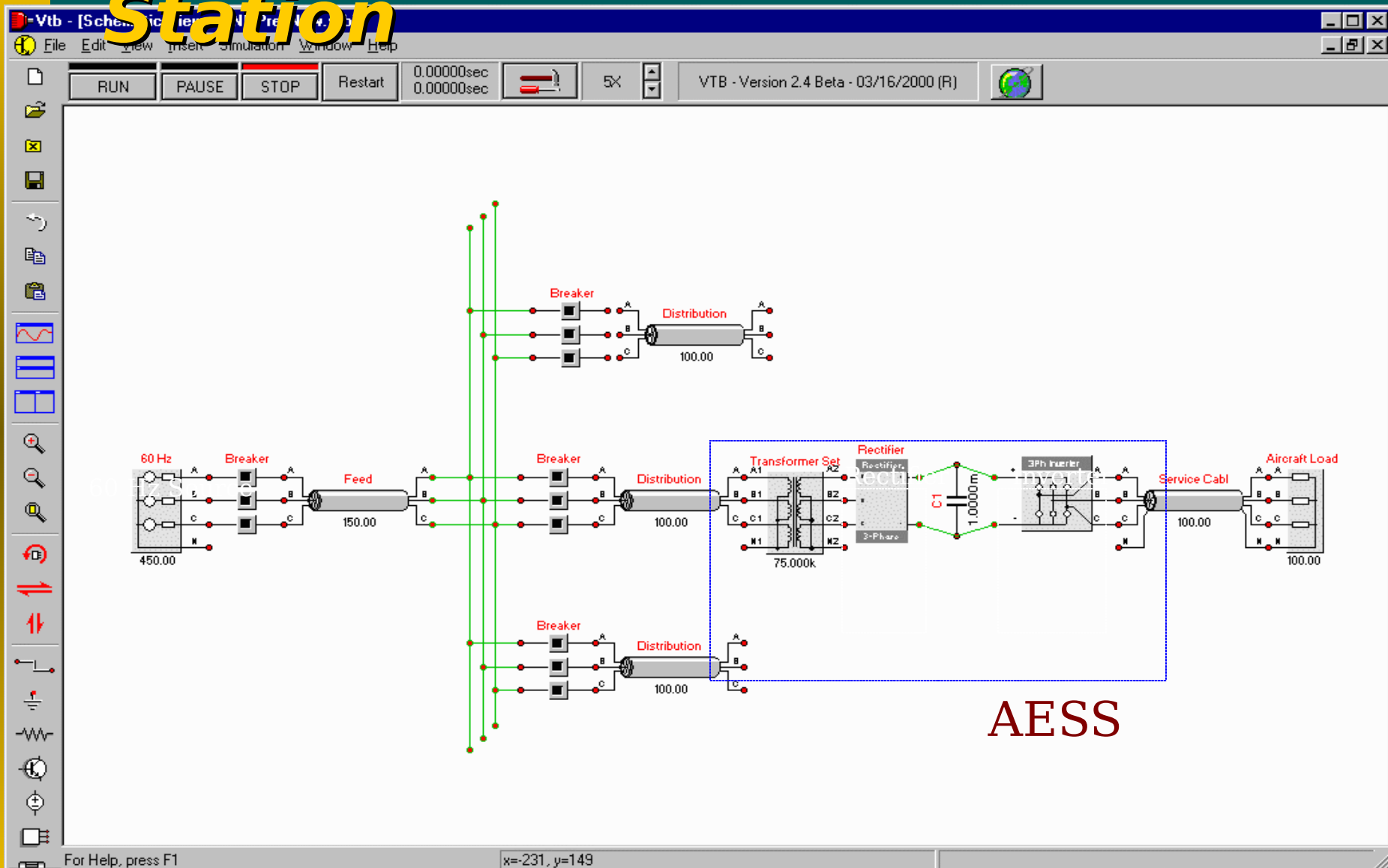
NORTHROP GRUMMAN

Electronic Sensors & Systems Sector

(NGMS)



Aircraft Electrical Servicing Station

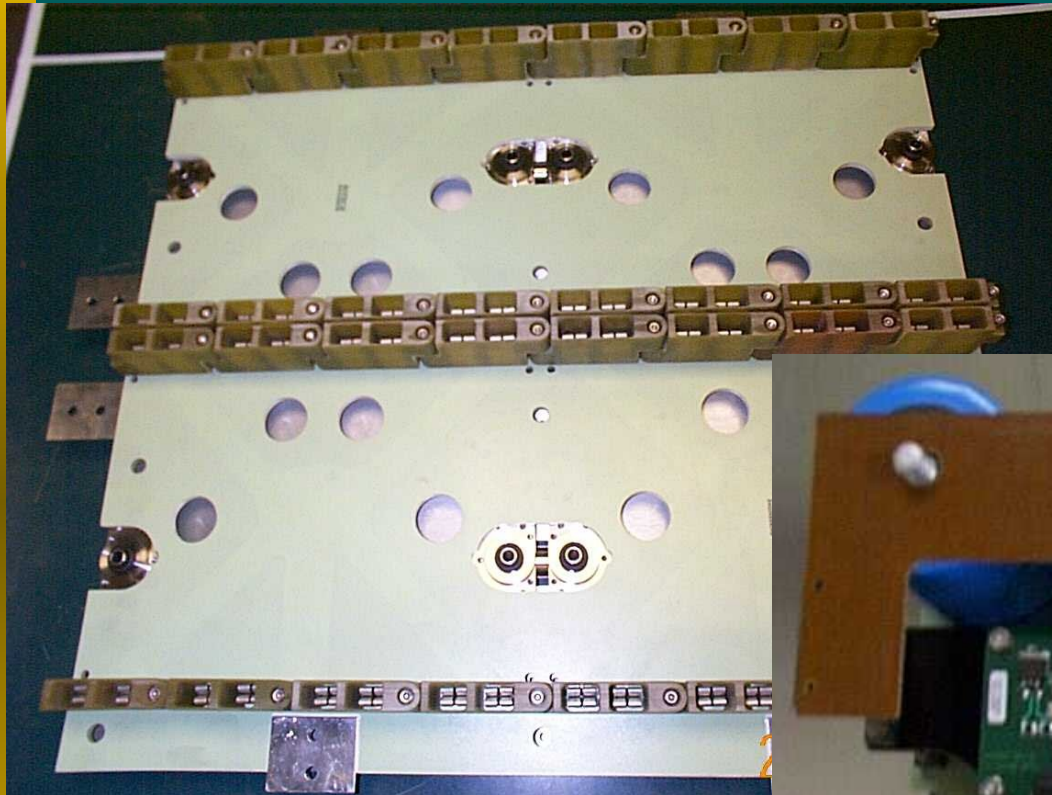


Partial VTB Conceptual Model - Proposed System

Aircraft Electrical Servicing Station Benefits:

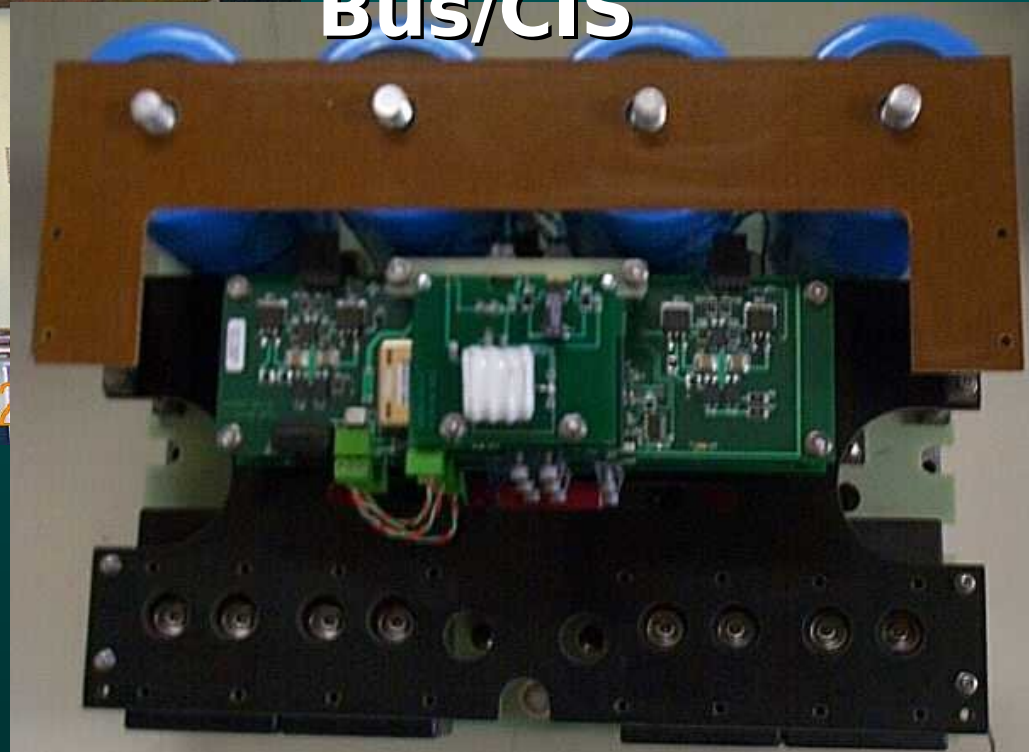
- **Affordability**
- **Replaces 400 Hz motor generators and line voltage regulators**
- **Reduces maintenance and increases reliability**
- **Performance**
- **Provides high-quality 400 Hz and 270 Vdc power to service both existing and future aircraft**
- **Additional Benefits**
- **Rapidly transitions PEBB technology from the lab into the fleet**
- **Demonstrates the potential of the Virtual Test Bed for simulation-based acquisition**
- **Demonstrates the effectiveness of an industry, government, and academic partnership**

Aircraft Electric Servicing Station (AESS) Technology



**Mounting
Base/DC
Distribution
Bus/CIS**

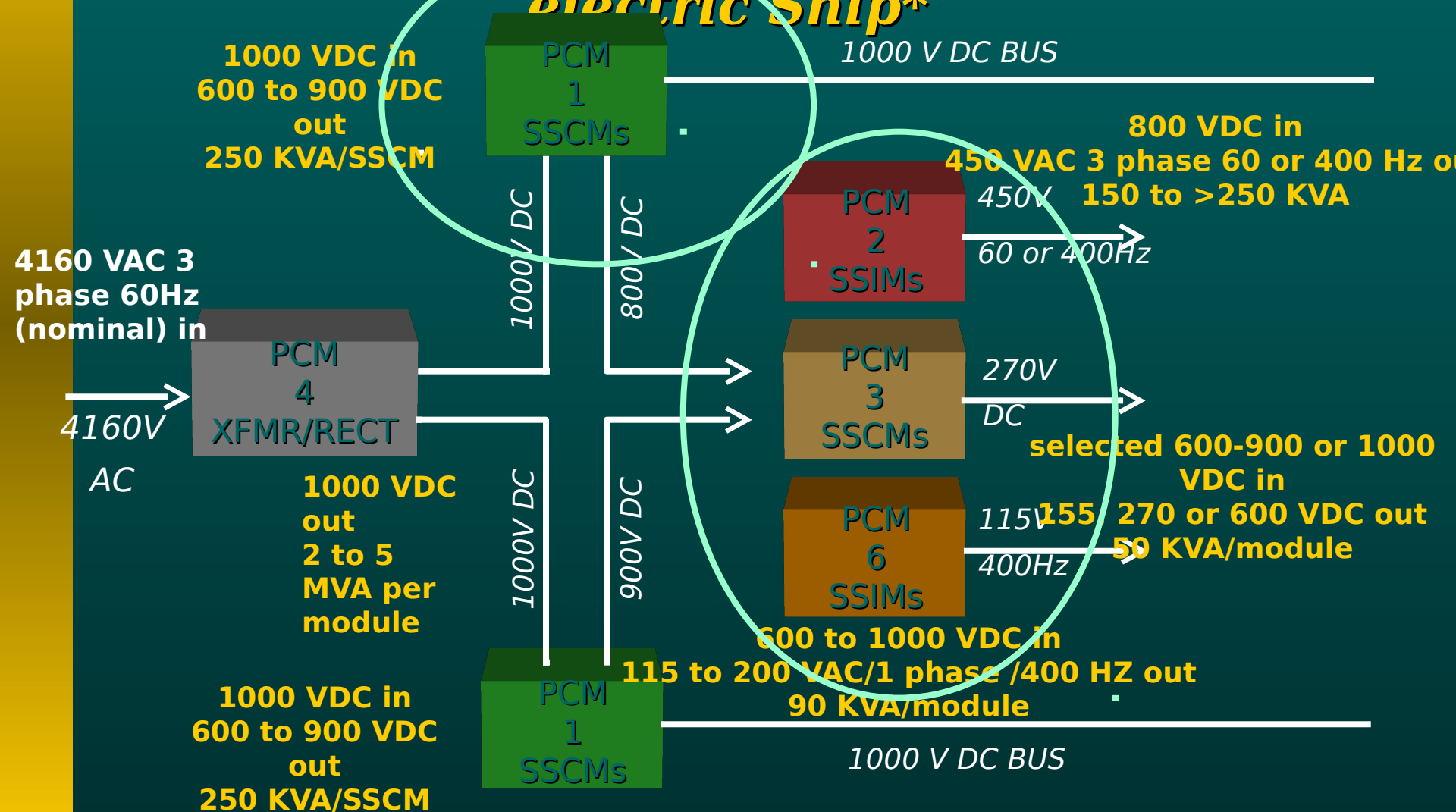
**Hard
Switch
Phase
Log**



Convert to soft switching with plug-in

Controller Quantitative Parameter Values Needed:

*Basic IPS DC ZEDS Architecture of an All-electric Ship**



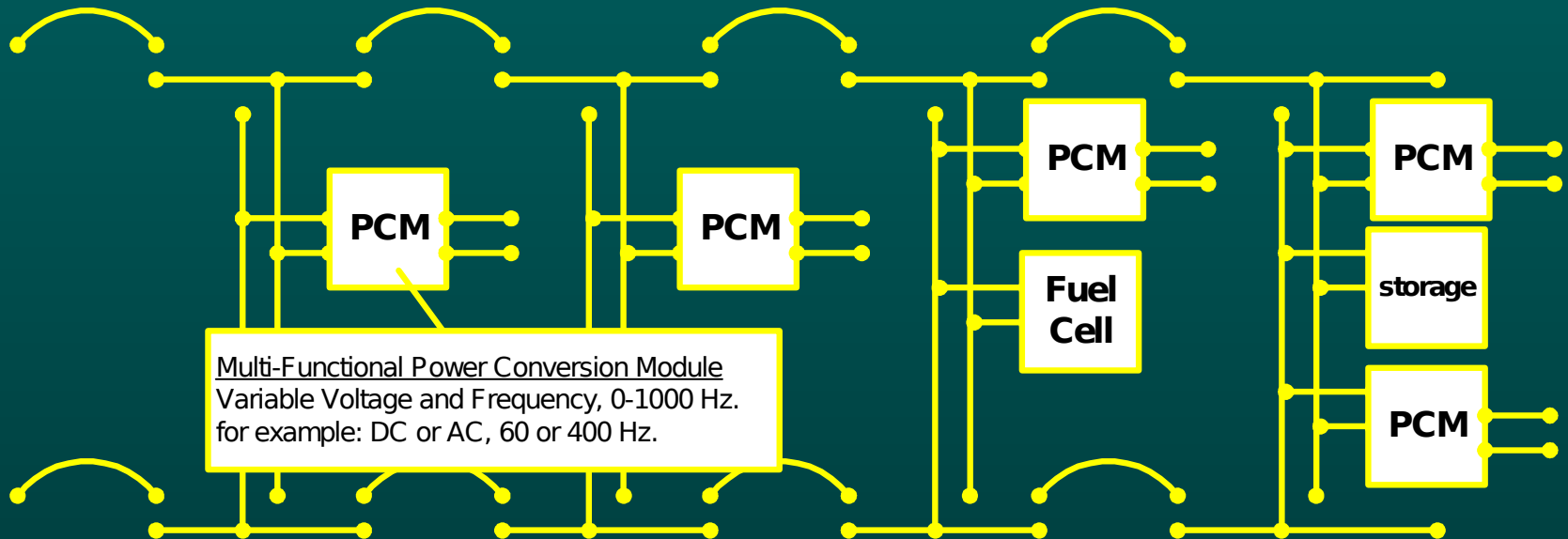
* Based on IPS Program studies

Point of Use Power Conversion

Low power quality bus

Disconnect/Limit

Dynamic Bus Regulator



Integrated Active-Filter Algorithms
Distributed generation and storage

Software Controlled Functions
Plug-in Modules based on power

Point of Use Power Conversion

- Eliminate conversion steps
 - Distribution
 - Weapons
 - Auxiliaries
 - Propulsion
- Increase efficiency and reduce cost
 - Distribution Efficiency could be 60-85% in DC Zonal
- Open Architecture Plug and Play, PnP
- Distributed generation and energy storage
- Flexible AC Transmission and Flexible DC Transmission alternatives

Shipboard Integration

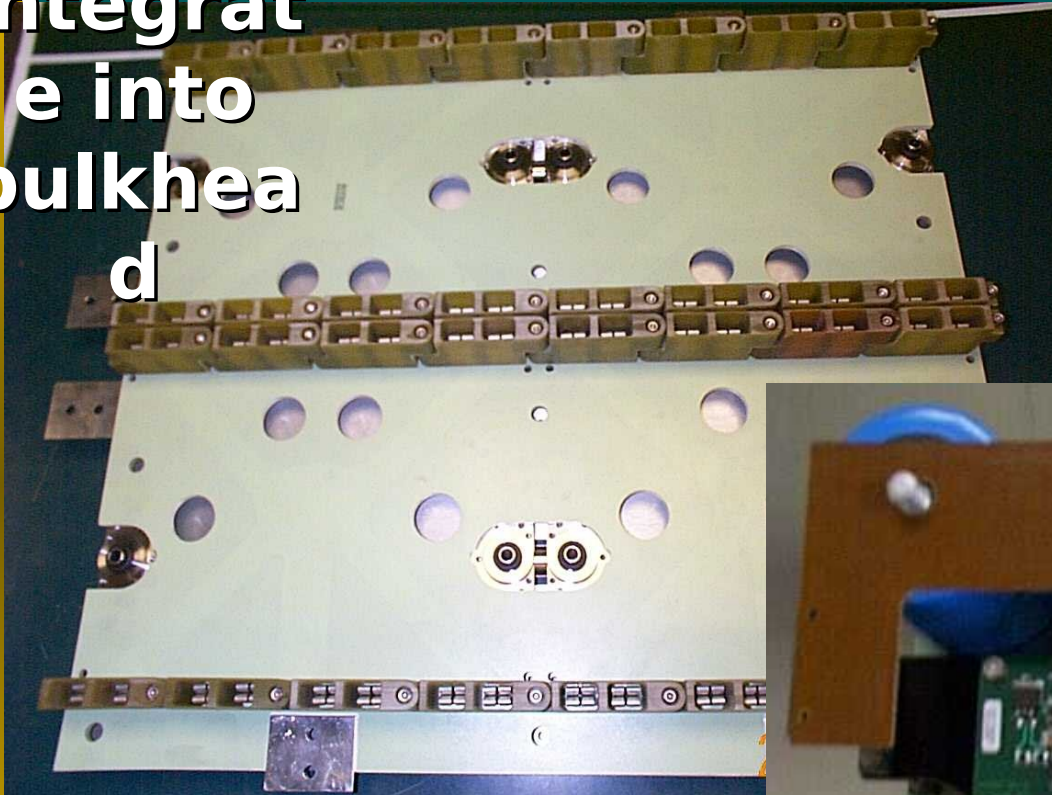
- Integrated Bulkhead -- electrical, thermal, and mechanical integration
 - Integrated power cooling
 - normal and alternate (redundant) cooling for increased survivability
 - Integrated fuel distribution for distributed generation
 - normal and alternate (redundant) cooling for increased survivability
 - normal and alternate fuel supply
 - Multi-Layer Bus Duct

A backplane is needed for Plug

AESS Technology as an Example of Future Shipboard Integration

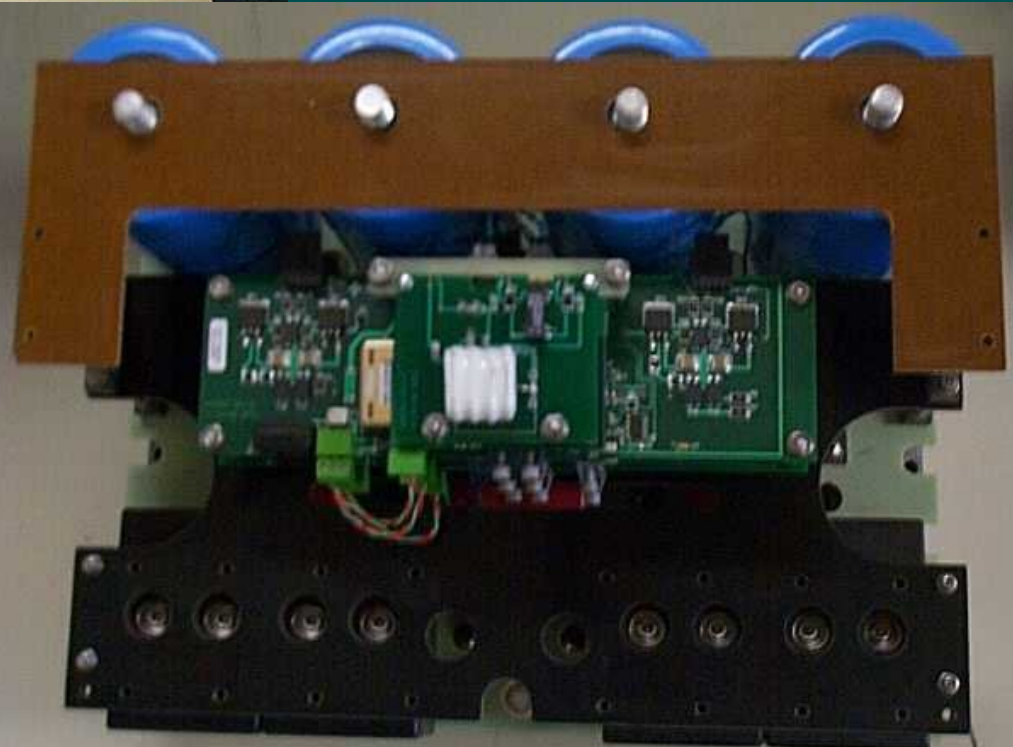
integrate into bulkhead

multilayer power-circuit board with integrated cooling

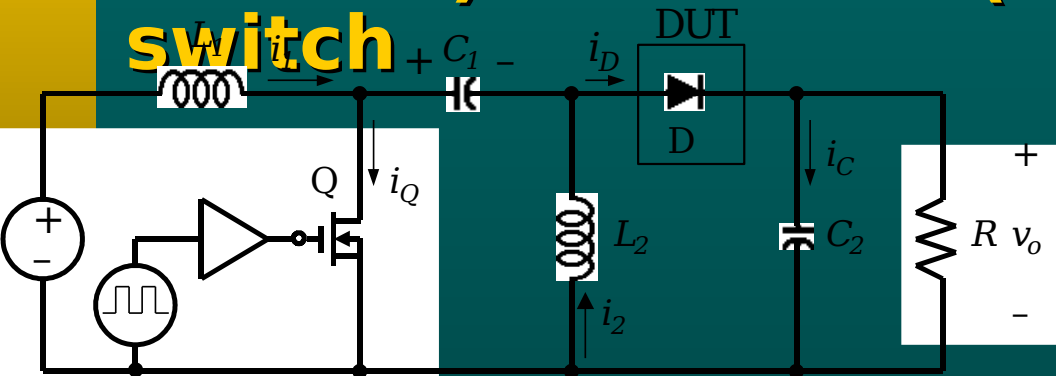


17" by 12" dual-inline package

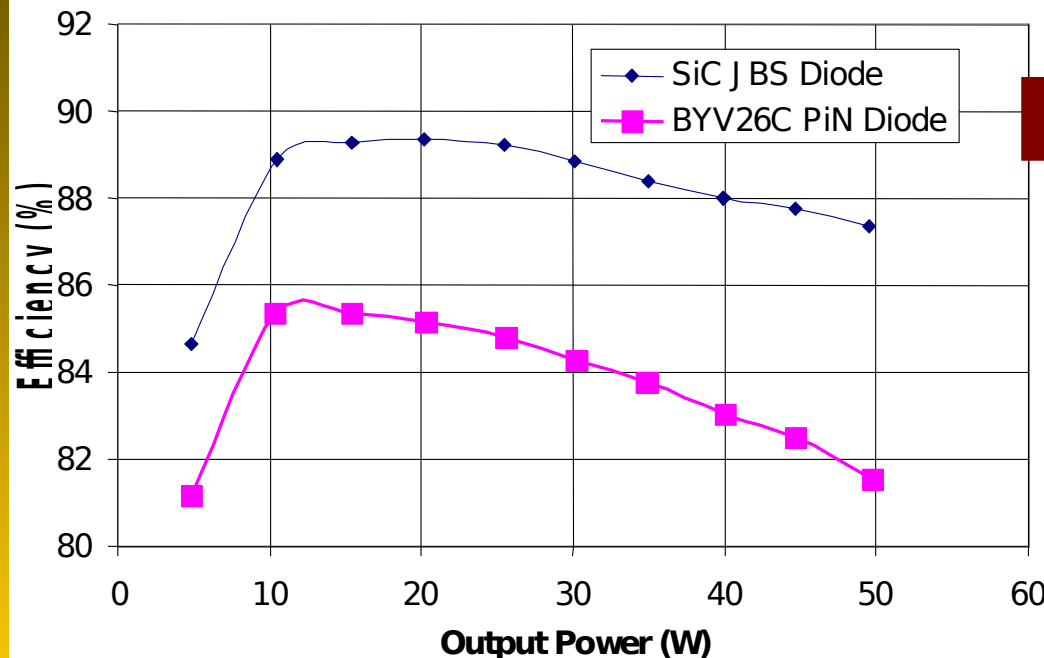
plug in as needed for compartment



Next Power Efficiency: DC-DC Converter with SiC (Silicon Carbide) Diode & Si (Silicon) CoolMOS switch



Circuit diagram of a DC-DC converter for efficiency evaluation with a 600V CoolMOS Switch



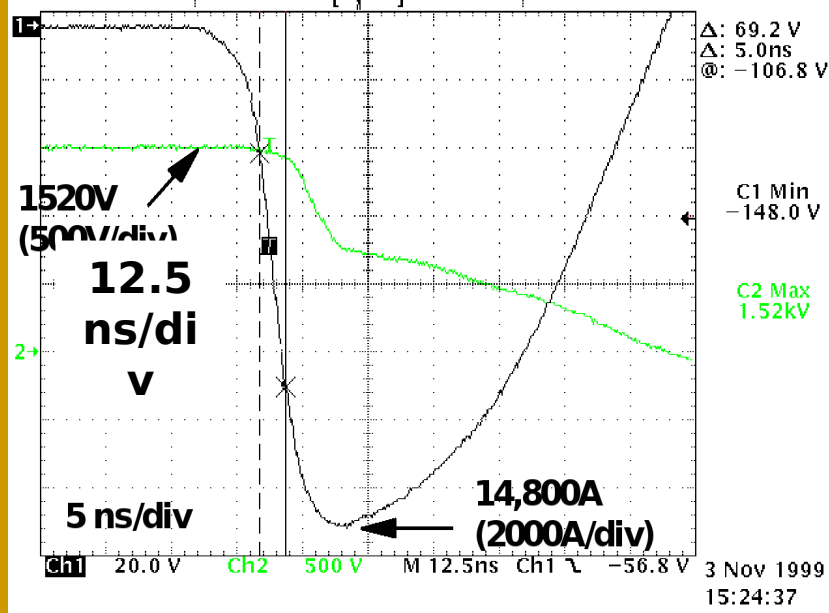
Increased Power Supply Efficiency

SiC JBS diode (1500V) vs. ultra-fast reverse recovery silicon diode (600V)

A. Hefner, Jr & D. Berning, NIST; J. S. Lai & C. Liu VA Tech.; R. Singh Cree Inc

On Switch -- Near Perfect for "Smart Munitions"

MCT's optimize speed, ThinPak optimizes packaging



Discharge test

Voltage: 1520V
Turn-on delay*: 16 ns
di/dt: 1,400,000 A/us
I-peak: 14,800 A

* From $V_g=0.0$ V to anode voltage = 90% of initial voltage.

Status:

<
2,000V

< 1cm²

Peak current density is 37kA/cm²
Peak di/dt density is 3.5 million

Military Comments

- Honeywell (Allied Signal) – POC Jay Desch
 - Honeywell has order 250 #6 MCTs from SPCO for use in their joint project with NSWC Indianhead. They are developing an anti-torpedo torpedo, and using MCTs as the firing trigger. Initial testing of the devices was described as promising. **Mr. Desch seemed overall very satisfied with the product and referred to it as the “Switch of choice” for this application.**
- ATK (Alliant Techsystems) – POC Jim Lucas
 - ATK is using the MCT in two Department of Defense projects. One for the Airforce called PLOCAAS, and the other for the Army called GMLRS. Again the MCT is being used for triggers for various armament. **Mr. Lucas seemed pleased with his testing of MCTs, referring to them as “a major improvement over existing technology.”**

Commercial Comments

“the right way to push power chips up the power curve is the concept being pioneered by the Office of Naval Research (ONR). The ONR’s Power Electronics Building Block (PEBB) program is focused on silicon and – above all—on developing a modular, plug and play design. ... Students of the history the microcosm will recall that the integrated circuit itself originated in an analogous program ...”
– The Huber Mills “Digital Power Report” Published by Gilder Publishing.

ABB Press Release

“Essentially, a PEBB is a pre-engineered power electronic device and control structure that may be used as a basic building block for a wide variety of applications such as inverters, drives, frequency changers and power quality products. The PEBB architecture is such that the mechanical overhead is minimized, stray inductances are lowered, and switching losses are reduced. So while the PEBB mechanical structure is "fixed", a specific application is determined by the manner in which various PEBBs are interconnected and how they are configured for operation by control software. **Thus due to their pre-engineered structure the ONR PEBB concept will permit efficient product development and a more affordable high power delivery product.**

One year into the program, ABB Automation is pleased to announce the development of a 9MVA PEBB and control platform considered to be the core of the ABB PEBB product portfolio. Werner Raithmayr, General Manager of the product responsible unit, ABB Power Electronics Systems in Switzerland stated "**we are pleased with the design flexibility of the ABB 9MVA PEBB and have already successfully used it as a standard foundation for two high power delivery applications. The first a frequency converter for an 18MVA rail application; the second a Dynamic Voltage Restorer (DVR) to protect a well renowned microprocessor manufacturing facility from un-acceptable power**

Definitions

AESS	Aircraft Electrical Service Station
ARCP	Auxiliary Resonant Commutated Pole
BJT	Bipolar Junction Transistor
EARS	Electromagnetic Aircraft Recovery System
EMALS	Electromagnetic Aircraft Launch System
ETO	Emitter Turn-Off Thyristor
FTO	Fast Turn-Off Device
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Controlled Thyristor
MCT	MOS Controlled Thyristor
MOS	Metal Oxide Semiconductor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MTO	MOS Turn-Off Thyristor
SCR	Semiconductor Controlled Rectifier
THD	Total Harmonic Distortion

Definitions Continued

ATR	Auto-Thermal Reformer	KW	Kilowatt
BA	Budget Activity	LABEVAL	Laboratory Evaluation
CO	Carbon Monoxide	MC	Molten Carbonate
D&I	Discovery & Innovation	MTI	McDermott Technology, Inc.
DOE-NETL	Department of Energy – National Energy Technology Laboratory	MW	Megawatt
DUST	Dual Use Science & Technology	NAVSEA	Naval Sea Systems Command
FC	Fuel Cell	NOx	Nitrous Oxides
FCE	FuelCell Energy, Inc.	NREC	Northern Research & Engineering Company
GTG	Gas Turbine Generator	ONR	Office of Naval Research
HC	Hydrocarbons	PEM	Proton Exchange Membrane
HPFC	High Power Fuel Cell	PR 03	Program Review FY03
IFP	Integrated Fuel Processor	S&T	Science & Technology
INEEL	Idaho National Engineering & Environmental Laboratory	SOFC	Solid Oxide Fuel Cell
IPS	Integrated Power System	SSFC	Ship Service Fuel Cell
IR	Infrared	USCG	United States Coast Guard